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HELMET DESIGN CRITERIA FOR IMPROVED CRASH SURVIVAL

By

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January 1966

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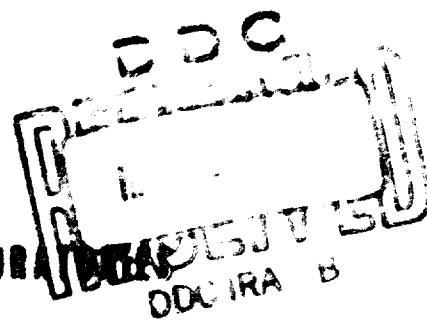
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CONTRACT DA 44-177-AMC-254(T)

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DEPARTMENT OF THE ARMY
AVIATION SAFETY ENGINEERING LABORATORY
FORT MONMOUTH, NEW JERSEY 08058

This report has been prepared by the Aviation Safety Engineering Division of the Flight Safety Foundation under the terms of Contract DA 44-177-AMC-116(T). The technical objectives of this contract were to develop engineering design criteria which will contribute to increased crash safety for the occupants and operators of Army aircraft.

This report deals specifically with the results of a study to develop improved head protection devices. The investigation was primarily devoted to a quantitative solution of the helmet shell and liner structural response, impact resistance, and energy-absorbing properties. Qualitative considerations were given to helmet retention, communications, and other related sub-systems. The method of testing is briefly analyzed and will be the subject of a more detailed follow-on study.

Conclusions and recommendations contained herein are concurred in by this command.

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**HELMET DESIGN CRITERIA
FOR IMPROVED CRASH SURVIVAL**

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SUMMARY

The major crash survival variables affecting the design and testing of U. S. Army aircrewmens helmets are presented and discussed in this report. Such factors as head acceleration limits, impact velocity, impact surfaces, impact sites, suspension and retention harnesses, helmet ventilation, impact test methods, and structural concepts are considered.

An examination of all available data on the tolerance of the human head to deceleration was conducted. Consideration was given to an analysis of acceptable design limits. A parallel study of head injuries occurring in aircraft accidents was conducted to determine the significant injury areas of the head and correlate this to protection area and techniques. A cockpit survey was conducted to develop criteria for testing the helmet and liner materials.

Consideration was given during the program to a preliminary investigation of helmet retention systems and head cooling techniques.

A series of instrumented drop tests was conducted to investigate various helmet design concepts and materials. Double-shell and single-shell helmets of nearly equal weight were analyzed.

The advantages and disadvantages of three different methods of helmet impact testing are discussed.

FOREWORD

The contractor performed all work listed herein, under the provisions of contracts DA 44-177-AMC-116(T) and DA 44-177-AMC-254(T), with the U. S. Army Aviation Materiel Laboratories*, Ft. Eustis, Virginia. Funds for this effort were provided to the U. S. Army Aviation Materiel Laboratories by the Natick Engineering and Research Center, Natick, Massachusetts, under obligation authority 64-18.

* Formerly U. S. Army Transportation Research Command.

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SYMBOLS

V	velocity at impact
a_A	peak acceleration recorded in cadaver impact tests
a_B	peak acceleration recorded in AvSER headform tests
Z_R	thickness of crushable helmet liner material
t	pulse duration
ΔZ	helmet liner compression distance
ϵ	strain at maximum helmet liner compression
σ	maximum compressive stress of outer liner
W	weight of head and helmet combination
F_s	force required to compress outer shell
K_1	constant equal to ratio of ϵ_{avg} to ϵ_{max}
K_2	constant dependent upon interaction between the energy absorber and the outer shell
A	area of helmet liner compressed

BACKGROUND

For a number of years, the U. S. Army has studied the problem of head protection for its aviators. The Army has, since 1954, used the All Purpose Helmet #5 (APH-5) developed by the Navy. The APH-5 helmet has reduced the number and severity of head injuries; however, the helmet is not devoid of operational deficiencies as has been amply outlined in a report entitled "Helmet Design Criteria"^{1*} under a previous U. S. Army study. Some of the concepts developed in this report are based upon the ideas developed in the previous study.

Several modifications to the existing helmet (APH-5) have been made by the Natick Engineering and Research Laboratories over the past several years. These consisted primarily of the following items:

1. A more shatter-resistant shell consisting of ballistic resistant nylon cloth rather than fiber glass cloth. The shell offers ballistics protection equal to that of a steel shell (M-1) dough-boy helmet; that is, protection for a fragment at 1,050 feet per second velocity. The fragment weighs 17 grains and is simulated by a caliber .22 steel truncated cone.
2. A redesigned adjustable nape strap to improve the retention capacity.
3. Nylon slides replacing metal slides, originally used for retaining the visor, so as to reduce the injury producing potential of these protuberances.

The changes referenced above have improved the APH-5 helmet. However, a review of the requirements for head protective devices leads to the conclusion that a system analysis of all pertinent parameters with an eventual synthesis of these parameters is necessary in order that new design criteria can be developed. This report integrates new structural concepts and materials with other factors pertinent to optimum head protection for aircraft accident situations.

*The superscript numbers refer to references listed on pages 60, 61, and 62.

CONCLUSIONS

The results of this study, together with certain assumptions, permit the following conclusions:

1. Protection for head impact onto rigid surfaces with velocities of approximately 20 feet per second can be provided with helmets of reasonable (1.25 inches) thickness.
2. The cushioning material and the design G level for a helmet are functions of the anticipated maximum impact velocity to be encountered "in service".
3. Design G levels, based upon presently available medical data, should be between 90G and 160G depending upon the helmet thickness and the factor of safety desired.
4. Protection against repetitive impacts in the same area of the helmet does not appear to be necessary. Provision for such protection would generally be undesirable because of the rebound characteristics of the elastic cushioning materials required to effect such protection.
5. Head protective coverage should extend downward to just above the eyebrow in the frontal area, just below the base of the skull (occipital) in the rear, and just below the ear canal (tragus) at either side.
6. The double-shell helmet as tested in this study offers better overall decelerative load protection than the presently used service helmets of equal weight.
7. The double-shell type helmets with annealed metal outer shells (aluminum and magnesium) produced lower rebound velocities than any of the other shells tested; therefore, if it is assumed that low rebound velocities are desirable, the annealed metal outer shells are preferable over all other types of shells tested.
8. The specification of stress-strain characteristics for energy-absorbing materials would be preferable to the current specification of foam density, because energy-absorbing foams of equal density may vary widely in their stress-strain values.

9. A net suspension system similar to that described in this report is comfortable as a result of low contact pressures and it appears adaptable to the application of forced-ventilation cooling systems.
10. A "collar-type" retention system, similar to that described in this report, appeared to offer good retention capability. This type of harness, whether it is fabricated from net or webbing material, is considered to be the best approach to a retention system.
11. While natural helmet ventilation will be helpful in moderate climates, severe conditions demand the use of forced ventilation and/or cooling for comfort.
12. A six-size, head-length and head-breadth system will significantly reduce the clearance between the head and the helmet as compared with a three-size system; however, the "net" retention system as used in this study appears to reduce the need for close helmet fit, and a three-size system is believed acceptable with a sling or net retention harness.

RECOMMENDATIONS

It is recommended that:

- 1. Further research be conducted on head acceleration limits with particular emphasis on (a) unconsciousness limits, (b) fatal limits, (c) the effect of pulse shape and duration on these limits, and (d) the effect of rebound velocity.**
- 2. A study be conducted to determine the physical requirements of helmet retention harnesses.**
- 3. Further research be conducted to establish an optimum test method to be used for qualifying test aircrewmen helmets with emphasis to be placed upon comparative results which will be obtained in using the fixed anvil and fixed head methods.**
- 4. Manufacturers of helmets using foamed-in-place materials be required to verify the stress-strain properties of the foam.**

APPROACH TO THE PROBLEM

The design of helmets for use by U. S. Army aircrews necessitates consideration of many requirements which have been established by the Army's operational experience with aircraft since World War II. These requirements were agreed upon by a Task Group composed of the pertinent Army agencies, which met in late 1961 and the early part of 1962. The requirements deemed necessary at that time are summarized below from the detailed reports of the conferences.

List of Helmet Requirements:

1. Helmet should be compatible with voice communications equipment and should provide attenuation against excessive noise.
2. Helmet should be compatible with an integrated sun visor.
3. Helmet should provide eye protection against nuclear weapons flash blindness.
4. Helmet should be compatible with oxygen and gas masks.
5. Helmet should provide ballistics protection.
6. Helmet should be comfortable. (This automatically dictates light weight and some method of cooling the helmet in high temperature environments.)
7. Helmet should provide crash protection.

Obviously, some of these requirements are contradictory; for example, complete ballistics protection is not compatible with light weight and comfort, that is, protection against .30 caliber ammunition. The integration of all these requirements into one helmet concept is a formidable task, which, in fact, appears to be attainable only by compromising some of the requirements. The approach taken in this study is to consider crash protection (the primary reason for the wearing of a helmet) as the first objective, with the full knowledge that the other functions can be added at the cost of increased weight and decreased crash protection. It is conceivable that two helmets, one for peacetime operation, and one for combat usage might be practical. The peacetime helmet would incorporate communications, while the combat helmet would incorporate other major features. Such an approach

would leave the student pilot, for example, unburdened with unnecessary helmet equipment. An analysis of the feasibility of developing two helmets was beyond the scope of this study and would be subject to many trade-offs (cost, logistics, etc.); therefore, the paramount consideration was directed towards crash protection.

ANALYSIS OF THE PROBLEM

As already noted, this report is concerned primarily with a study of crash (impact) protection; however, the other factors which have a direct bearing on helmet design are considered. Each of the items previously listed in Approach to the Problem (page 3) is discussed briefly in Appendix I. All of the available literature pertinent to the design of aircrewmen helmets was reviewed. A summary of the literature which was considered as background information for this project is included in the bibliography. The bibliography has been used as appropriate in this report.

In order to achieve a crashworthy helmet as well as a comfortable helmet for aircrewmen, several factors must be correlated. These factors are as follows: (1) the impact velocity, (2) head tolerance to deceleration, (3) nature of the impact surface, (4) the probable location of the impact on the head, (5) suspension methods, (6) retention methods, and (7) sizing (fit). The first four factors are discussed in this section. Suspension methods, retention methods, and sizing methods are discussed in Appendices IV, V, and VI. Helmet comfort and cooling are also relegated to Appendix VII since they affect impact protection only indirectly.

The impact testing of helmets to determine their compliance with crash protective design requirements is also of primary interest; therefore, an analysis and discussion of various testing methods is included in Supplement I.

IMPACT VELOCITY

Very little is known about the relative velocity of the head and the striking surface in aircraft accidents. Since this variable obviously affects helmet design, it was necessary in this study to take an indirect approach to determine impact velocity limits. This was done by considering (1) the maximum relative velocities that can be permitted when reasonable helmet dimensions are maintained, (2) the impact protection provided by the existing APH-5 helmet, and (3) the velocity changes which are admissible from the human tolerance standpoint in short duration impacts as discussed in the Head Acceleration Limits section (pages 10 through 16).

An approximate correlation between the velocity change and helmet thickness (more accurately, the crushable material thickness) at given acceleration levels is shown in Figure 1. The material thickness given in this figure is based upon an assumed rectangular acceleration-time pulse; thus, the thickness given is the minimum which would be acceptable even with ideal conditions. Note that the material thickness required to absorb the energy of the moving head at 40 feet per second, with an acceleration level of 100G, is about 5 inches. This thickness is obviously impractical since an increased helmet thickness carries with it a two-fold penalty of increased weight and increased size.

The weight of the helmet must be minimal for optimum comfort. Minimum weight may also be a factor in reducing head and neck injuries in accidents. The weight of the human head for a 50-percentile man is approximately 11 pounds; the existing APH-5 helmet weight is approximately 3.7 pounds, and the proposed ballistic-resistant nylon helmet weighs over 4 pounds. Thus, the ratio of helmet-to-head weight currently is about 40 percent. A discussion of the APH-5 weight by Captain Richard E. Luehrs of the U. S. Navy in a recent helmet symposium⁵ indicates that Navy pilots in aircraft carrier ditching accidents are seen sitting in an intact restraint harness, making no attempt to extricate themselves before the aircraft sinks. It has been theorized that the 40-percent increase in head weight with the corresponding high inertia loads in the neck is contributing to unconsciousness of pilots in these accidents.

The upper limit on the size of the helmet appears to be governed by (1) cockpit size limitations, (2) visual limitations, and (3) operational comfort. The cockpit size of U. S. Army aircraft does not appear to be a limiting factor; however, detailed measurements would be required using 95th percentile personnel seated in the smallest cockpits to determine this limitation. The accepted visual requirement of 15 degrees upward from the horizontal limits the frontal thickness to about 3 inches for a helmet fitted just above the eyebrows. Helmets of excessive dimensions impose high neck torsional moments in rapid rotations of the head, inducing fatigue.⁶ Thus, from a standpoint of helmet weight and size, the impact velocity is limited.

It is shown in Appendix II that when the APH-5 helmet was retained in place during an impact, head injuries were reduced by about 65 percent. An Air Force study indicates a similar reduction of injuries for fliers wearing helmets.⁷ The energy-absorbing liner of the APH-5 is about 9/16 inch thick. Thus, some increase in thickness beyond this value is desirable if optimum protection is to be provided at the impact velocities

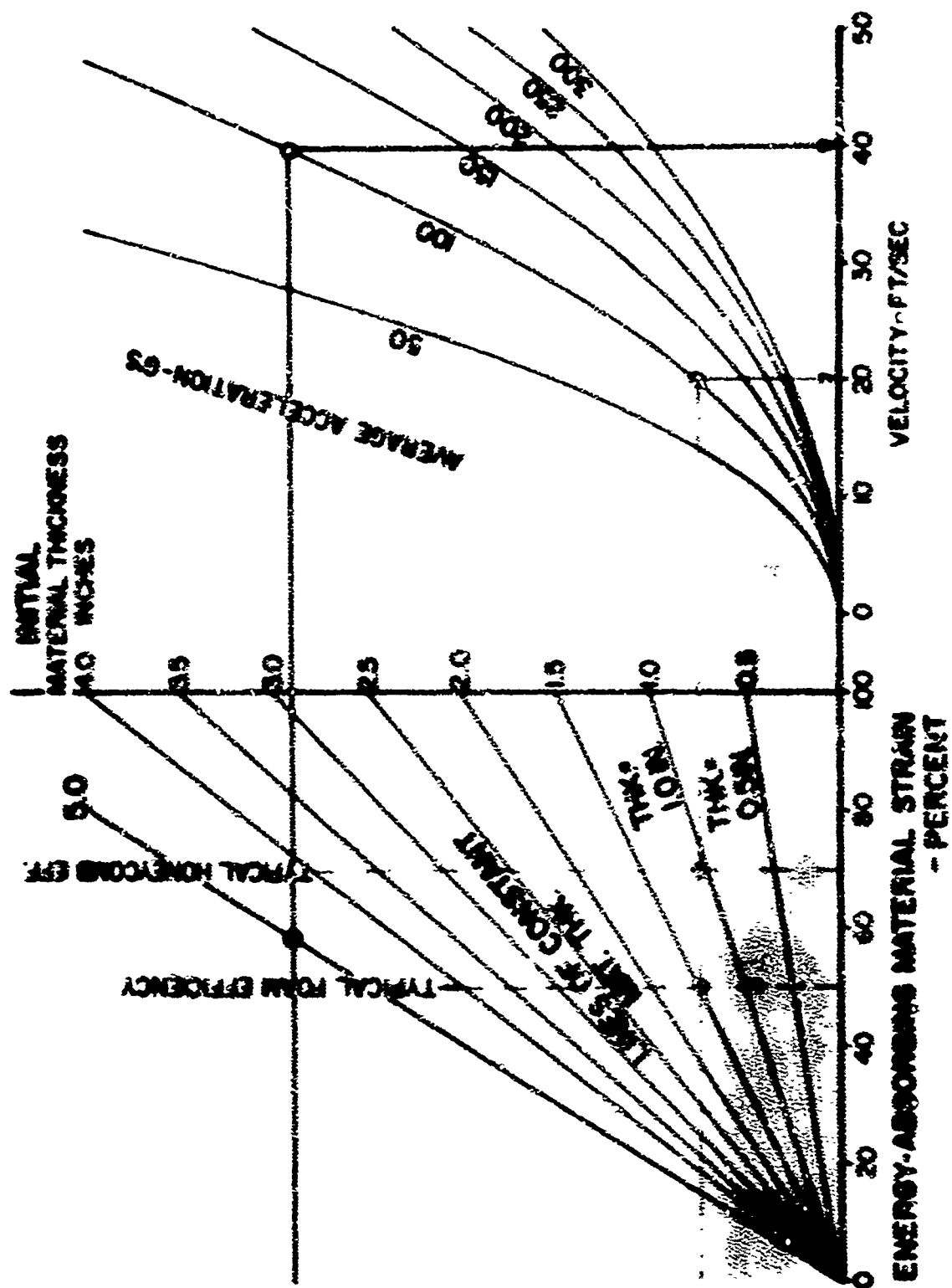


Figure 1. Crushable Material Thickness as a Function of Velocity Change and Acceleration Level.

occurring in accidents similar to those which have occurred in the past.

The foregoing discussion, while indicative of the effects of impact velocity upon helmet dimensions, does not fix numerical values for the pertinent variables. The helmet thickness as a function of impact velocity, when head acceleration limits are considered, is discussed in the following section.

HEAD ACCELERATION LIMITS

Research on head tolerance to accelerative loads has resulted in the publication of numerous papers in this field. The purpose of this section is to review briefly a number of key references in order to determine design acceleration values for aircrew helmets. The reader is referred to the Head Acceleration Limits section of the bibliography for a comprehensive listing of publications.

Before discussing the maximum acceleration values which the head can sustain without injury, mention should be made of the effect of the rate of change of acceleration (da/dt) sometimes called the rate of onset of acceleration or simply onset rate. This effect on acceleration limits has not been clearly established. An acceptable acceleration onset rate probably lies somewhere between 20,000 and 200,000G per second. The former value is declared acceptable by the New York State Boxing Commission for the materials used in boxing platforms while the latter is quoted by Rawlins as an upper limit.¹¹ A value of 100,000G per second may be admissible; however, use of lower values is certainly desirable until the effect of this variable on head tolerance is more firmly established.

Early efforts to determine the resistance of the body to decelerative forces are exemplified by DeHaven's "Mechanical Analysis of Survival in Falls from Heights of Fifty to One Hundred and Fifty Feet"⁸ published in 1942. This study indicated that the whole body (when impacted transverse to the spine) could survive average accelerations of 150G for short periods (0.010 to 0.012 second). In view of the relatively flexible neck-to-torso attachment (approximately 10G maximum resistance) it seems logical to assume that the head sustained an acceleration equal to that of the whole body in the above falls and that this range of head acceleration is survivable.

Dr. Gurdjian and his associates at Wayne State University, Detroit, Michigan, have conducted extensive experiments to determine the mechanism of brain injury both with cadavers and live animals; their work on skull fracture and concussion appears to be in agreement with injuries sustained in accidents involving the living human. Dr. Gurdjian and co-workers assumed that "since many cases of linear fracture in clinical experience are associated with an unconscious state, it was felt that when a linear fracture was obtained, in a human cadaver, a moderate to severe concussive effect would also occur";⁹ thus, the data obtained in the fracture of cadaver skulls were correlated with animal concussion limits and human clinical data to obtain the acceleration-time curve shown in Figure 2. This curve is a plot of the average acceleration versus the total period of the impulse required to approach unconsciousness limits as discussed in reference 9.

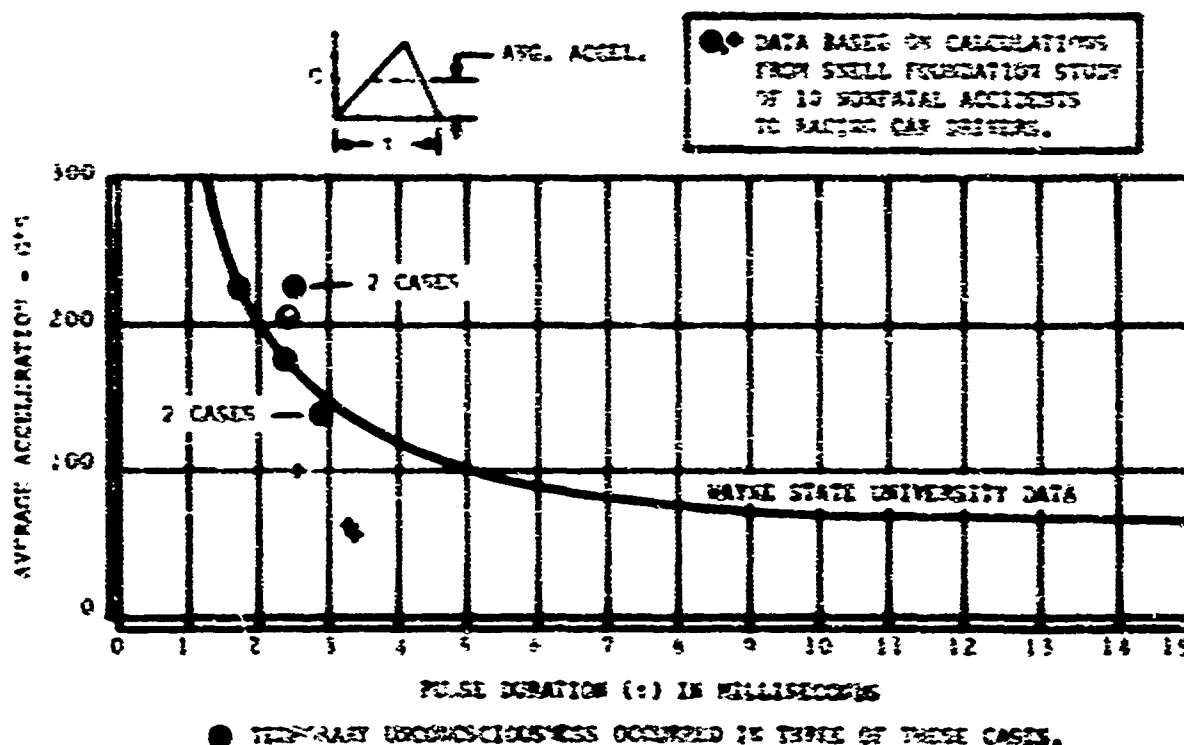


Figure 2. Comparison of Wayne State University Head Acceleration Data With Snell Foundation Data.

Dr. Snively of the Snell Foundation, Sacramento, California, has arrived at survivable head acceleration limits through the correlation of nonfatal head injury cases with helmet damage.¹⁰ Laboratory tests

were conducted using dummy headforms wearing helmets identical to the protective gear which had been involved in actual accidents. By measuring the accelerations produced in the laboratory in impacts resulting in the same helmet damage as for the accidents, an approximation of the accident pulse was obtained. His paper unfortunately included the maximum liner deflection and acceleration only; however, in discussions with Dr. Snively, it was established that the pulse shapes involved were nearly triangular. Assuming this to be the case and also assuming that the maximum liner deflection during loading was 20 percent greater than the liner deflection value recorded, the pulse times were computed. These data points are superimposed on the cadaver test data of Wayne State University in Figure 2. Obviously, no great reliability can be placed on this data because of the approximations made in obtaining it. The data does, however, indicate agreement with the tolerance curve of Dr. Gurdjian and his colleagues.

In order to establish a design acceleration level for energy-absorbing helmets, the human limits to decelerative loads and the practical limits of helmet thickness must be correlated. The following analysis, although only approximate because of (1) the limited data available on accelerative limits to head impacts and (2) the assumptions made with respect to pulse shape and its effect on head acceleration tolerance, does illustrate the basic relationships between the pertinent variables.

The acceleration-duration relationship as obtained in the Wayne State University tests on cadavers ^{9, 12} is shown in Figure 3. In this plot (curve 1) the accelerations (a_{avg}) and pulse duration (τ) are those illustrated in Figure 4A. Based upon a triangular pulse shape*, the maximum acceleration a_A is twice the average acceleration as shown in curve 2 of Figure 3.

Curve 2 in Figure 3 thus gives the peak acceleration versus the complete pulse duration based on the triangular pulse. It is not known whether head tolerance to pulses of other shapes can be extrapolated from curves 1 and 2; however, for the purpose of this analysis, it is assumed that pulses which do not differ greatly from the basic triangular pulse and which possess the same energy per unit mass (same velocity change) will cause similar damage to the human brain.

* In communications between the authors of this report and L. M. Patrick, co-author of reference 12, it has been established that the pulse shapes obtained in the cadaver tests were very nearly triangular in shape.

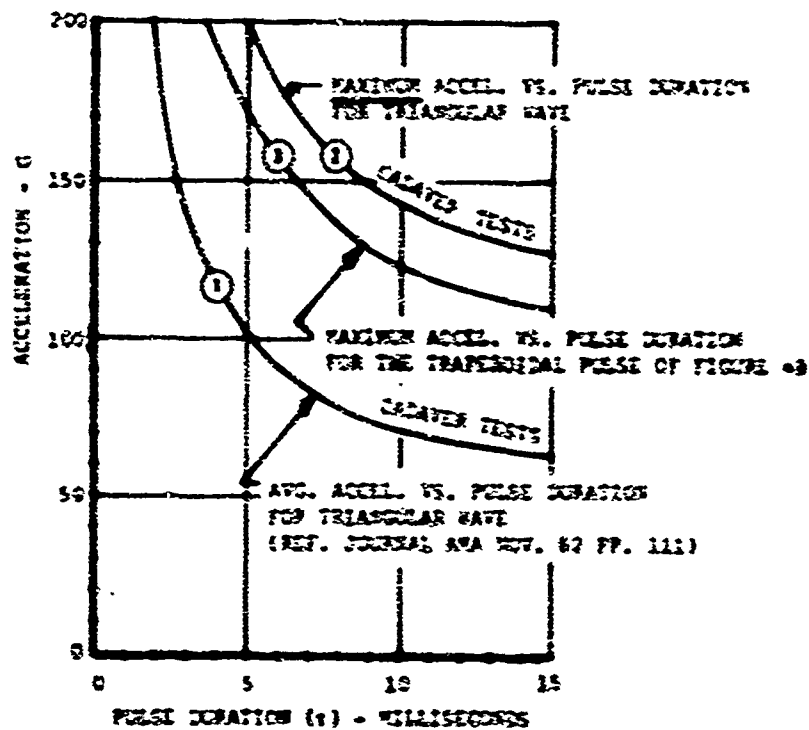


Figure 3. Acceleration-Time History in Humans, Based on Head Impacts on Cadavers, Animals, and on Clinical Observations of Humans.

Figure 4B illustrates a typical pulse as obtained in the experimental tests described in this report.

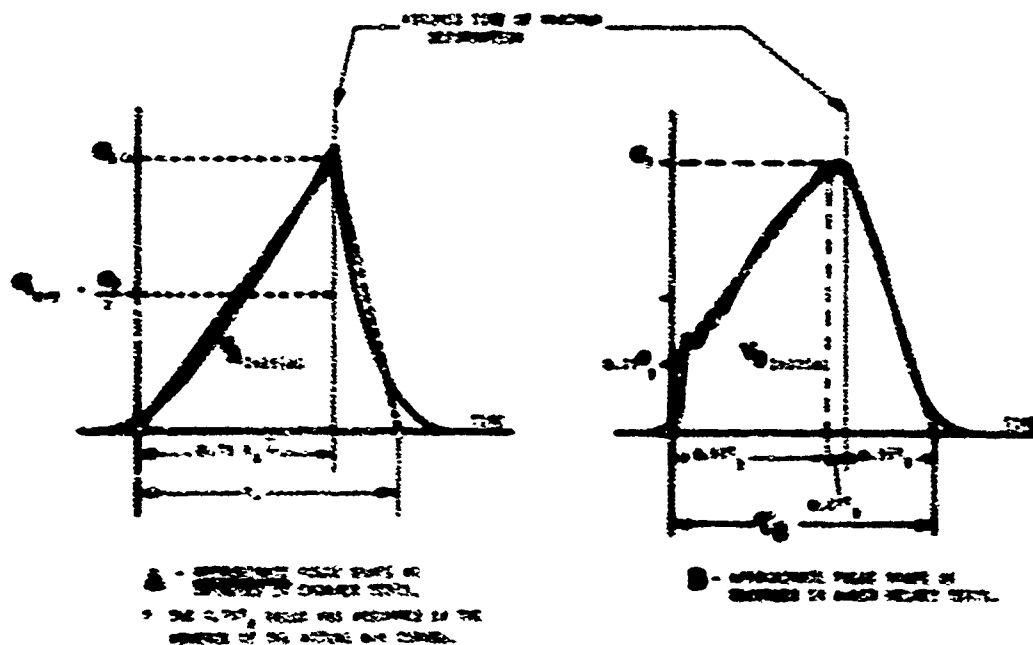


Figure 4. Shapes of Pulses Used in Human Tolerance Study.

The approximate human tolerance to this pulse is then found as described below.

Letting

V = Velocity at Impact

a = Peak Acceleration

τ = Pulse Duration

A, B = Subscripts associated with Figures 4A and 4B,

then, from Figure 4A,

$$V_{A_{\text{initial}}} = \frac{0.75}{2} a_A \tau_A = 0.75 a_{A_{\text{avg}}} \tau_A \quad (1)$$

From Figure 4B,

$$V_{B_{\text{initial}}} = a_B \frac{(1 + 0.25)}{2} (0.60 \tau_B) + a_B (0.37 \tau_B) = 0.41 a_B \tau_B \quad (2)$$

Since $V_A = V_B$ for equal energy, equating equations (1) and (2) gives

$$a_B = 1.70 \frac{\tau_A}{\tau_B} (a_{A_{\text{avg}}}) \quad (3)$$

and, for pulses of equal period,

$$a_B = 1.70 a_{A_{\text{avg}}} \quad (4)$$

This equation is plotted as curve 3 in Figure 3 and it is the approximate tolerance curve for the pulse of Figure 4B.

The helmet compression distance (Δ_B) can now be computed giving

$$\Delta_B = 0.177 a_B \tau_B^2 \quad (5)$$

Since Δ_B in the above equation is the maximum deflection during compression, it is more meaningful to express equation 5 in terms of initial helmet thickness Z . Let the strain at maximum compression be ϵ , then

$$A_B = \epsilon Z_B$$

$$\text{and } Z_B = 0.177 \frac{a_B^2}{\epsilon} \quad (6)$$

Equation (6) is plotted in the upper portion of Figure 5 for three values of ϵ . The maximum impact velocity as given by equation (2) is plotted against the helmet design G level in the lower portion of Figure 5.

The following comments can be made from an examination of these curves:

1. The slope of the "thickness versus design acceleration" curve is such as to make the design acceleration quite sensitive to the initial helmet thickness. For example, a change in helmet thickness from 0.5 inch to 1.5 inches for a safety factor of 1.0 and $\epsilon = 0.75$ would imply a change in the design acceleration from 160G to 115G.
2. To provide protection at the largest possible impact velocity, a large helmet thickness in the region of the impact is required. The design acceleration level, however, should be lower than that for the thinner helmets.
3. Complete protection against brain damage at very high head impact velocities can probably never be achieved in a helmet of reasonable thickness (2 inches or less). This fact suggests that, if maximum protection against head injuries is to be accomplished, very careful consideration must be given to the materials used in the helmet and to the details of its design and construction. It is recognized that larger velocity changes can be permitted for impacts against a yielding surface rather than a rigid surface.

It should be noted that the relation between initial helmet thickness and the design G level as given in Figure 5A provides for no factor of safety based upon concussion (unconsciousness); that is, with these design levels, unconsciousness subsequent to the impact is probable. Design acceleration levels which could result in unconsciousness may be satisfactory for some helmet users, such as racing car drivers, in which other personnel are immediately available to extricate the occupant in case of postcrash fire or other hazards. For aircraft occupants, however, ultimate survival often depends upon the ability of the individual to evacuate the aircraft rapidly and without aid. Thus, helmet design G levels which may result in unconsciousness appear to be undesirable.

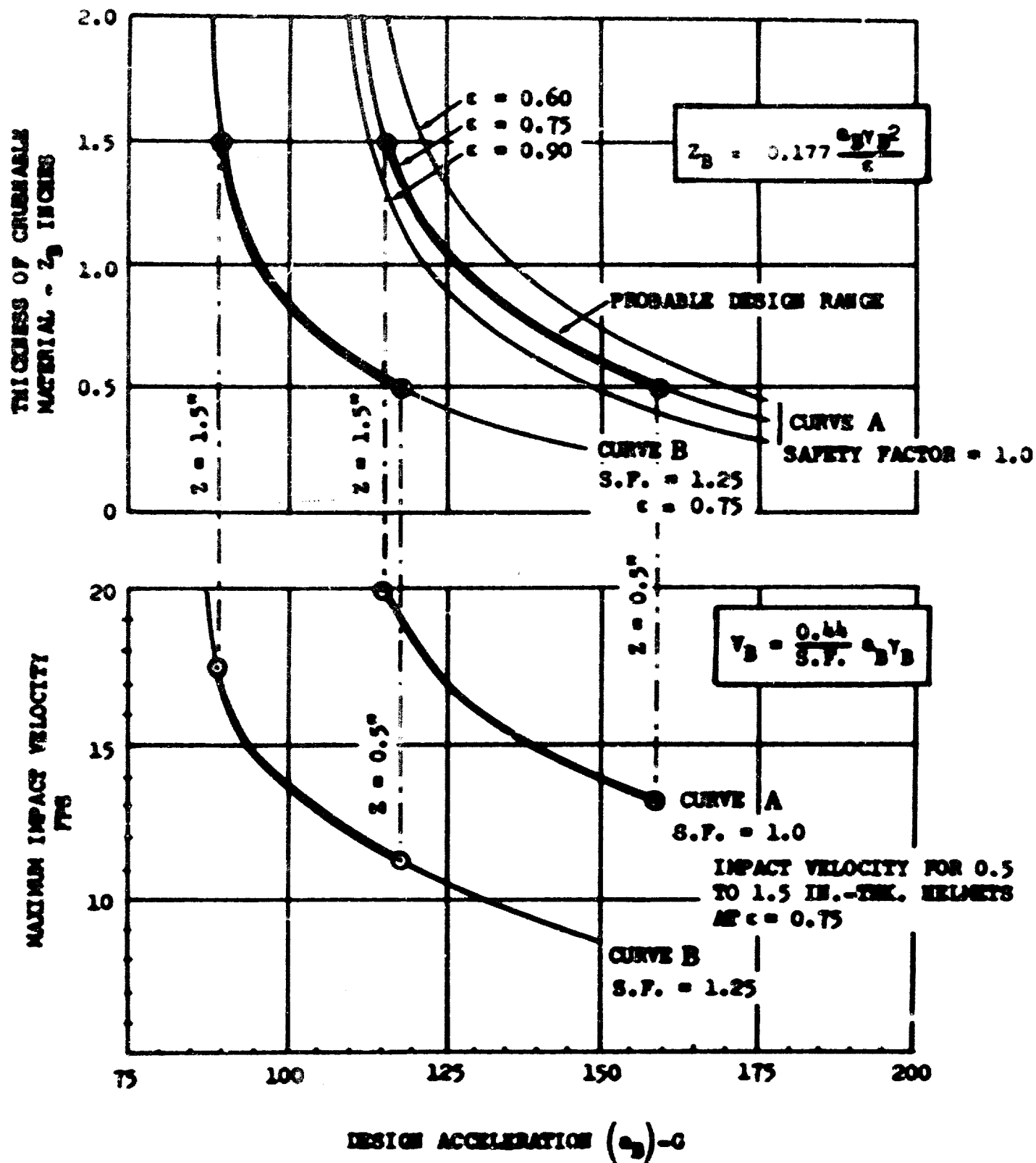


Figure 5 Maximum Impact Velocity and Helmet Thickness as a Function of Helmet Design Acceleration.

What safety factor should then be applied? An accurate answer depends upon several factors which can be obtained only from a statistical study of (1) the exact nature of the head injury threat for each type of aircraft with emphasis on the probable impact surfaces and relative velocities to be encountered, (2) the variation in tolerance of the individual, and (3) the true importance of unconsciousness as related to evacuation and ultimate survival. Such a study is beyond the scope of this report.

In the absence of further information, it was assumed during the construction of the experimental helmet described in the section on test results that a safety factor of 1.25* (based upon the tolerance curve of Figure 3) would be satisfactory for aircrewmen helmets. The experimental model was designed to achieve the design acceleration of 0.80 times the concussion limit when impacting a 90-degree-corner surface. This permits impact on a flat surface without exceeding the concussion limit, since the ratio of the accelerations for a flat surface and a corner is approximately 1.25 for helmets of the type of construction used for the experimental article.

The B curves of Figure 5 show the effect of introducing the 1.25 safety factor. A 1-inch-thick helmet (assuming $g = 0.75$) can provide the desired protection up to an impact velocity of 14.5 feet per second compared to the original value of 17.0 feet per second. For 2 inches of initial helmet thickness the corresponding impact velocities are 19.5 feet per second and 22.1 feet per second. The helmet with the 1.25 safety factor would permit some overshoot of the maximum strain of $g = 0.75$ before concussion begins for those cases in which the impact velocity is in excess of the theoretical design value. This would help to narrow the impact velocity advantage of the 1.00 safety factor helmet. Protection of the head at much larger velocity changes appears to be much more easily accomplished by protection of the entire body, that is, an adequate body restraint system which allows the entire torso to decelerate by the medium of crushing aircraft structure. The Army is currently considering the strengthening of aircraft personnel restraint systems up to the limits of whole-body accelerations.¹³ Thus, the occupant should be retained in place in future accidents rather than being ejected from the aircraft or into surrounding structure, as has occurred frequently in the past. Less head protection should be needed with the improved restraint systems.

* Reduction of the design acceleration level by a factor of $1/1.25 = 0.80$.

The experimental helmet described in this report contains a 1.25-in.-thick average thickness in the frontal portion. Figure 5 shows the design acceleration level to be 93G for a 1.25 safety factor or 120G for a safety factor of 1.00.

The reader must be cognizant of the assumptions made in the foregoing analyses when accepting or quoting specific numerical values obtained. Modifications to the assumptions, particularly with respect to non-injurious acceleration limits, and with respect to pulse shape and its effect upon tolerance level, will modify the final values to some extent. The general conclusions, however, will probably remain unchanged.

IMPACT SURFACES

In order to determine the type of impact surfaces which can be expected in the cockpits of Army aircraft, an examination of eight different aircraft was conducted and the results of this study are included in Appendix III. The results are summarized below for reader convenience.

Three basic impact shapes were revealed: (1) flat surface, (2) 90-degree-corner surface, and (3) a "box-corner" surface. The flat surface was noted in various areas of the cockpit, such as the instrument panel, windows, and bulkheads. This surface will give the highest acceleration level to the head, since a larger area of energy-absorbing material is crushed upon contact, thereby producing a larger stopping force. Since nearly half of the head impacts occur on the instrument panel and windshield in U. S. Army aircraft accidents, as revealed in the Appendix II study, the flat impact should be considered carefully in fixing design acceleration values.

The corner surface was seen in various areas of the cockpit, such as overhead wing beams, vertical support columns, window frames and door frames. The radii of these surfaces varied from 0.0625 inch to 0.25 inch; however, the thickness of the aluminum was generally less than 0.10 inch. Since these thin structures are expected to yield somewhat upon impact, a rigid radius of 0.25 inch appears to be reasonable, and this value was selected for the testing of helmet specimens in the experimental phase of this study. The imprint in a Navy flyer's helmet from a corner surface in an accident can be seen in Figure 6; it illustrates a typical corner impact.

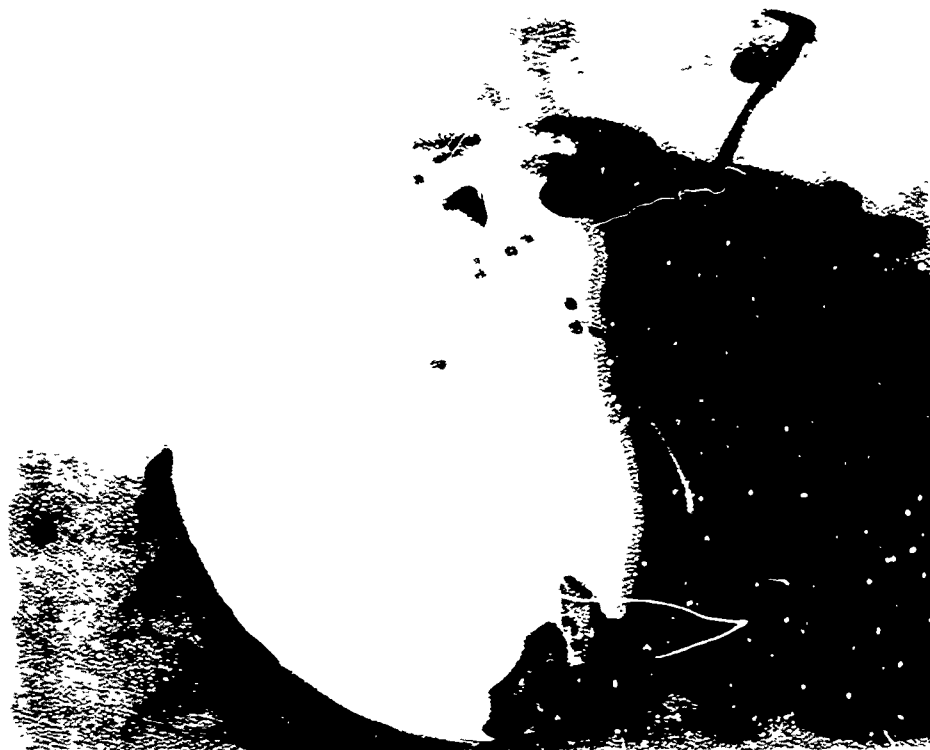


Figure 6. Imprint in a Navy Flyer's Helmet from a Corner Surface.

The box-corner surface was noted primarily in helicopter consoles in which the surfaces contained a radius of about 0.06 inch in one plane and about 0.38 inch in the other plane. It was decided to simulate this surface with a 90-degree cone for simplicity of drop weight construction. A radius of 0.06 inch on the apex of the cone was selected to allow a check of the puncture resistance of the helmet to broken or sharp structures, such as control columns, control wheels, knobs, bolts, etc. Thus, the cone test simulates impact with sharp-cornered objects, as well as broken or jagged structure.

IMPACT SITES ON THE HEAD

Data on head injury sites have been listed previously for civilians who were involved in lightplane crashes for the years 1942 through 1951 (see reference). More recent data have been collected in this report and are included in Appendix II. This study included 896 cases of civilian, Army, Navy, and Air Force head injuries which have occurred in light aircraft (up to 29,000 pounds) from 1952 through 1963. The results indicate that the majority of the injuries are occurring in the frontal area of the head and that a much lower percentage are occurring in the occipital (aft) area. Although a large percentage of impact sites

can be noted in the facial area, these blows are less likely to be fatal because it is shown that only 12 percent of the head injury fatalities result from impacts in the facial area. Injuries of the facial area should obviously be prevented, if possible; however, coverage of this area with a shield for the purpose of crash protection alone does not appear to be practical until a cooling system is developed which will alleviate the perspiration problem. The use of a nose and mouth guard, similar to that used on football helmets, may be practical, especially since the guard could also serve as a support for a microphone. The use of an open frame type face guard should be given further consideration.

In view of the small number of impact sites which occur in the temporal area below the tragus (ear canal) location, it appears reasonable to provide protection to the head only above this point. The elimination of protection below this point will accomplish the following: (1) reduce helmet weight, (2) improve the ventilation of the helmet, and (3) ease the placement and removal of the helmet.

On the basis of the head injury study in Appendix II, the following head coverage is recommended for U. S. Army air crewmen:

1. Frontal - Energy-absorbing liner should extend downward to a distance of 0.50 inch above eyelash level.
2. Aft (occipital) - Energy-absorbing liner should extend downward to the base of the occipital bone.
3. Lateral - Energy-absorbing liner should extend downward at least to the tragus point or possibly to one inch below this point.

Since the majority of head injuries are occurring in the frontal area, and since these injuries are also expected to be the most severe in view of the expected torso kinematics in aircraft accidents, it appears reasonable to taper the thickness of energy-absorbing material from the front to the back of the helmet. In the absence of data on the relative severity of impacts to the various regions of the head, it is suggested that the helmet thickness be about one-half of the frontal thickness in the crown and temporal areas and about one-third of the frontal thickness in the occipital area. The tapering of the helmet thickness from front to rear lowers the helmet center of gravity and overall weight.

Probability of Repetitive Impacts in the Same Area

The probability of receiving repetitive impacts in a given area of the helmet in most aircraft accidents appears to be remote. A review of the nature of aircraft accidents indicates that single roll-overs occur frequently, but that multiple roll-overs and cartwheels occur infrequently. A study of the civilian aircraft accidents in Appendix II indicated that only 4 percent resulted in cartwheel action. Fixed-wing aircraft are generally confined to single roll-overs because of their geometry, that is, the fixed-wing aircraft has a long wing and a long fuselage in comparison with its low height; therefore, once the impact occurs, the aircraft tends to skid on its belly, or flip and skid on its back. With helicopters, the aircraft is more prone to roll laterally; however, the rotor blades tend to prevent a large number of roll-overs. Only 3 roll-overs are recorded for the 37 Army helicopter accidents reviewed in the Appendix II study. Thus, the dynamics of aircraft in accidents suggest only single head impacts in a given area.

In some severe aircraft crashes, the restraint system fails and the crewmen are thrown through or out of the aircraft structure; but even in these cases the helmet is usually damaged more from contact with aircraft structure than from contact with the ground, trees, or rocks. The maximum energy appears to be absorbed in the initial contact with the aircraft structure, and the subsequent strikes occur at lower impact velocities except in rare cases.

On the basis of the above discussion, it does not seem necessary to provide protection against multiple impacts to the head in the same area for aircrewmen.

DESIGN CONCEPTS AND MATERIALS

There are two primary structural configurations for head protective devices. One type of construction consists of a rigid outer shell with a low-density, energy-absorbing material placed between the shell and the head. A second method consists of a double shell with a low-density, energy-absorbing material located between a ductile outer shell, and rigid inner shell. These concepts are illustrated in Figure 7.

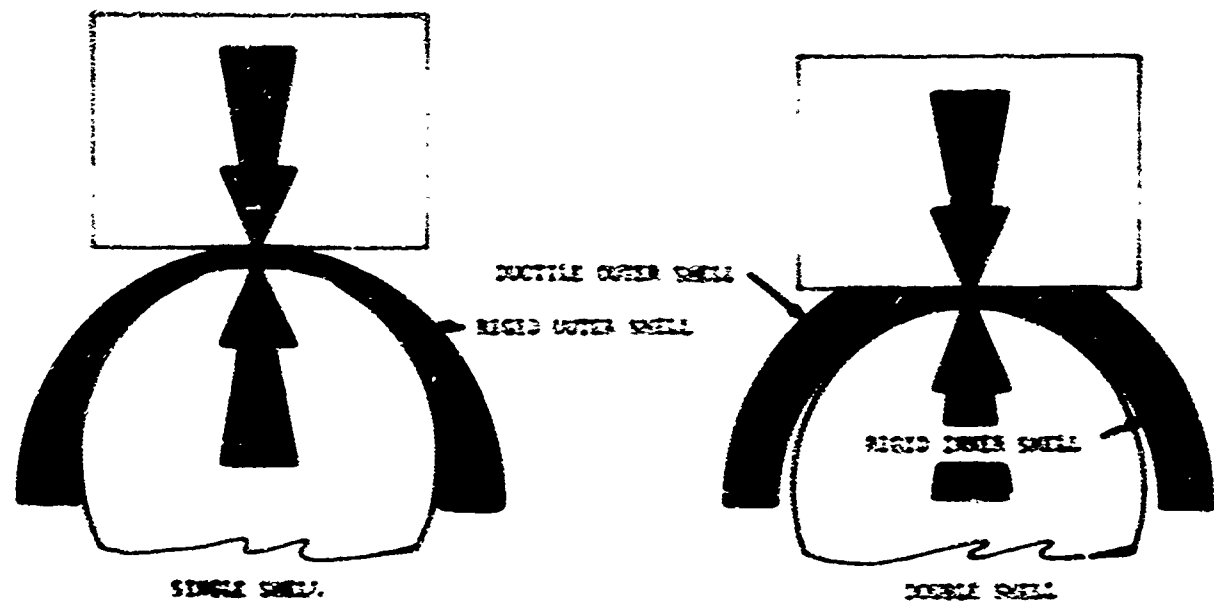


Figure 7. Comparison of Impact Deformation Between Single- and Double-Shell Concepts.

Regardless of construction methods, the helmet designs should incorporate materials which contribute to minimum rebound velocity, because it has been shown previously that head acceleration limits are a function of the impulse time, and rebound energy adds to the total pulse time. Thus, rebound energy should be kept as low as possible.

SINGLE-SHELL CONCEPT

When a rigid outer shell is used, a large area of energy-absorbing material is compressed as the head moves toward the shell, as shown in Figure 7. The shell must be thick in order to resist penetration and to maintain its contour with minimum deformation. A truly rigid

single-shell helmet appears to offer the following advantages:

1. It resists repeated strikes in the same location, since the outer shell does not deform after the first impact. This advantage for resisting repetitive blows requires an energy-absorbing material which, when compressed, returns to its original thickness at a sufficiently low rate to partially eliminate elastic rebound of the head subsequent to the impact. Such a material is referred to as a slow-rebound material. (This capability is not considered necessary for the one-impact aircrewman's helmet.)
2. It offers minimum resistance to rotation due to snagging on sharp surfaces. (This advantage has generally been negated by the attachment of a sun visor and other exterior protuberances on the APH-5 helmet.)

The following disadvantages for the single shell can be stated:

1. More shell weight is required to achieve uniform pressure distribution on the skull than is required for a double-shell helmet. (This point is illustrated by a comparison of the test results on hemispherical specimen number 17 with the other specimens in Table 3.) Specimen 17 was the only specimen which resulted in a depression greater than 0.04 inch for the standard, 4-foot drop test with a 90-degree-corner impactor.
2. A hard, rigid outer shell creates a higher moment of inertia for the helmet than for a double-shell helmet of equal crash protection. This can increase wearer fatigue due to the torsional force required to rotate the helmet during normal operation.
3. The single shell offers less resistance to crushing loads which are applied from both sides of the helmet simultaneously.

Helmet construction up to the present has been along the lines of the rigid outer shell concept. As a result, the shell has become rather thick and heavy in order to provide sufficient stiffness to prevent concentrated pressure on the skull at the point of impact.

DOUBLE-SHELL CONCEPT

The use of a double shell will achieve good load distribution (sufficient stiffness) at a lower weight than with the single shell. As already stated,

the inner shell of a double-shell helmet serves as a pressure distributor during the planned deformation of the outer shell and the crushing of the energy-absorbing liner. An outer shell to serve as a load spreader* when struck by sharp objects is necessary; however, this outer shell must be thin enough to prevent excessive acceleration levels when impacted by flat surfaces. The inner shell can serve as the attachment platform for the retention harness, thus placing the harness close to the surface of the head. This will improve retention of the helmet in severe impacts.

A helmet incorporating the above concepts in its design should yield the following advantages:

1. The lowest weight with adequate load distribution.
2. The lowest rebound velocity for a given helmet weight, because the outer shell is thinner and stores less energy than a thicker single shell concept.
3. The lowest moment of inertia due to the thicker shell being nearer the head.
4. A more efficient retention system due to its attachment to the inner shell close to the head.
5. Increased resistance to crushing loads applied across the helmet.

The disadvantages for the double-shell concept appear to be:

1. The thin outer shell will snag more easily when struck by sharp components than would a hard, rigid outer shell.
2. The double-shell helmet will probably be more expensive to manufacture than the single-shell helmet because it is more complex.

The advantages of the double-shell helmet seem to outweigh its disadvantages for helmets to be used by airmen. The low weight of the double shell is believed to be far more important than the greater snagging potential of the thin outer shell, since the probability of impact on sharp components in the cockpits of new U. S. Army aircraft should

*Some energy is also absorbed in deforming the ductile outer shell.

be very low. Thus, this study has been devoted to developing the double-shell concept, with particular emphasis on selecting a combination of materials to give good overall protection.

Materials for a single-shell helmet would require different characteristics than for the double-shell device. Specific requirements of the single-shell concept are not evaluated in this report; however, the design should logically follow these general guidelines: (1) the outer shell should be relatively thick and rigid in order to uniformly distribute the impact force over a large area, and (2) the compressive strength of the liner material should be lower than for a double-shell helmet since a larger area of material is compressed.

The energy-absorption capacity and penetration resistance of a double-shell helmet are governed by the selection of four different components as listed: (1) inner energy-absorbing liner, (2) inner shell, (3) outer energy-absorbing liner, and (4) outer shell. The requirements for each of the above components are discussed separately.

INNER LINER MATERIAL

The inner liner should be a slow-rebound material, since its purpose is the absorption of low-energy impacts which may occur in hard landings, severe turbulence or other impacts of a repetitive nature. These repetitive impacts must be absorbed by a material which produces tolerable head accelerations. Lombard has shown that head accelerations of 20G to 30G in impacts at 4.6 to 6.5 feet per second result in frequent local bruising, pain, and headache.²² Thus, it appears that the inner liner material should not create an acceleration of more than 20G if the voluntary tolerable limits, as set by Lombard, are not exceeded. The area of contact between the frontal head and the semiresilient liner is approximately 16 square inches for a 1/8-inch deformation into a collapsible material.

Since the inner liner material is not compressed equally over the contact area, the compressive stress-strain curves must be examined to determine the average compressive stress, because the average value will vary in accordance with the shape of the stress-strain curve. For example, a material with a rectangular (flat) curve would not need a correction since its average stress, regardless of deformation, is equal to its maximum stress. On the basis of a 16-square-inch area in the frontal region, an average compressive stress of 14 psi should yield the desired 20G deceleration.

The stress-strain curves of several commercially available, slow-rebound foams are shown in Figure 8. Of the materials shown, the type AH Ensolite (Polyvinyl chloride - PVC foam, U. S. Rubber Co.) is the most desirable in view of the fact that it will result in a 20G acceleration at a maximum deformation of 1/8 inch in the frontal head area. The H-334 Koroseal (PVC foam, B. F. Goodrich) exhibits a flatter load-deformation curve than the Ensolite; however, its crushing stress is higher than desired. The Ensolite material was selected for all the hemispherical specimen tests because of its desirable compressive stress level.

The thickness of the inner liner must be based upon (1) the expected impact velocities in normal usage (noncrash) and (2) the thickness of outer liner material which must absorb the major (crash) velocity changes; that is, if only 1/4 inch of energy-absorbing space is available between the head and the helmet, it should obviously be filled with a material which crushes at an acceleration level nearer the tolerance values (100 to 175G) given by Figure 5 than at a level of 20G. If the total thickness of crushable material is one inch or above in the critical frontal areas of the head, then it seems reasonable to use 20 to 25 percent of this thickness for the inner liner. Thus, a thickness of 1/4 inch was used for the hemispherical test specimens and the experimental helmets. The 1/4-inch inner liner will easily absorb a minor impact of about 4-foot-per-second-velocity change.

The H-334 material in a 1/4-inch thickness was used in the experimental helmets; however, this material is not recommended unless its compressive stress level can be reduced to the same range as that of the Ethafoam and Ensolite shown in Figure 8.

INNER SHELL

The primary structural property of the inner shell should be good flexural rigidity combined with minimum weight. An examination of the mechanical properties of reinforced plastics and heat treated metals indicated that fiber glass bonded with epoxy would offer the maximum tensile strength per unit weight. A heat treated, 7178 aluminum alloy of 63,000 psi tensile strength or steel of 245,000 psi tensile strength would be almost equal to the strength to weight ratio of fiber glass; however, the ease of forming experimental samples dictated the use of the fiber glass for this study. The initial test of hemispherical specimens was conducted with two plies of 0.01-inch-thick fiber glass (4 ounces per square yard);

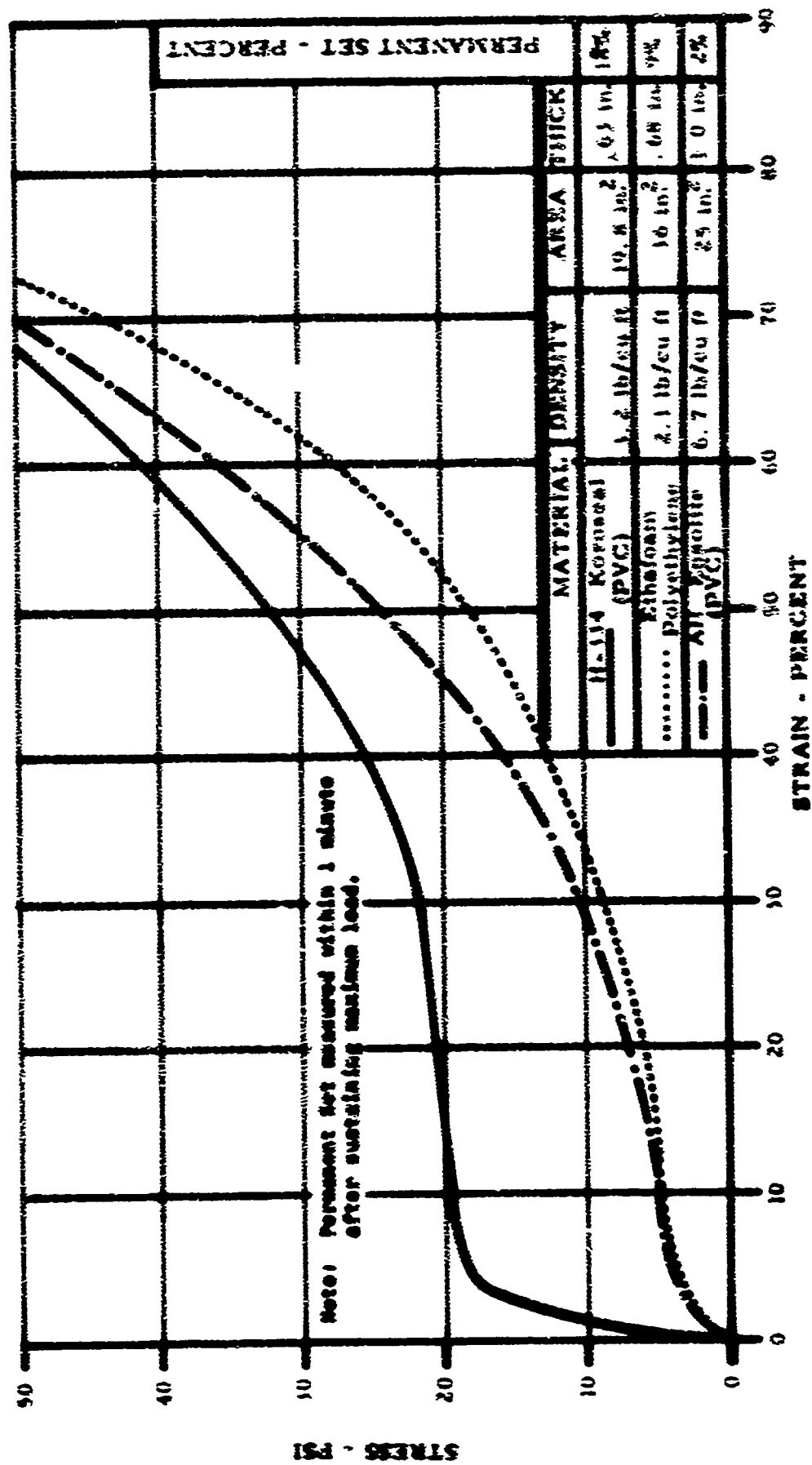


Figure 8. Stress-Strain Data for Commercially Available Slow-Rebound Foams.

however, this thickness was changed to three plies of the same material in subsequent tests to increase its rigidity. The experimental helmets (see Figure 15) were constructed with four plies of the same material in order to improve the resistance to penetration by sharp objects.

OUTER LINER MATERIAL

A review of the literature reveals three basic types of energy-absorbing materials: (1) nonresilient honeycomb constructed from thin sheet material, (2) expanded, semirigid plastic foam, and (3) expanded, non-rigid slow-rebound foams.

The stress-strain curves for representative samples of honeycomb and semi-rigid foam materials are shown in Figure 9. From the standpoint of energy absorption,* the optimum material is the nonresilient honeycomb (as exemplified by the aluminum flexcore material), since its crushing stress is maintained more nearly uniform during deformation and the "usable strain" range is in excess of that for the foamed plastics. The polystyrene or the polyurethane foams, however, offer acceptable stress-strain characteristics. Some experimental plastic foams which have been developed by the U. S. Army Natick Engineering and Research Center indicate excellent stress-strain characteristics for energy absorption²³; however, since this foam (identified as Plastic 0103.15) was not available commercially, it was not used in this study.

A review of Figure 9 indicates that the polystyrene material is far superior to the polyurethane for energy absorption; however, the reader must be aware that the data on the styrene foam was obtained from a Dow Chemical Co. sample of "styrafoam", while the urethane foam was obtained from a local plastics company because urethane samples in the correct density could not be obtained. A 1.9-pounds-per-cubic-foot density sample of Thurane (polyurethane foam), Dow Chemical Co., was obtained and tested and it yielded a flatter stress-strain curve than either the styrene or the urethane foam shown, but its average compressive stress was too low for this application. Thus, polyurethane should be equivalent to the polystyrene as an energy absorber when it is mixed in a higher density. The polyurethane foam was used for the tests described herein because local plastic shops were more familiar with its foaming characteristics. The inefficiency of the urethane foam

* The energy absorption for a unit volume of a material is equal to the area under the stress-strain curve.

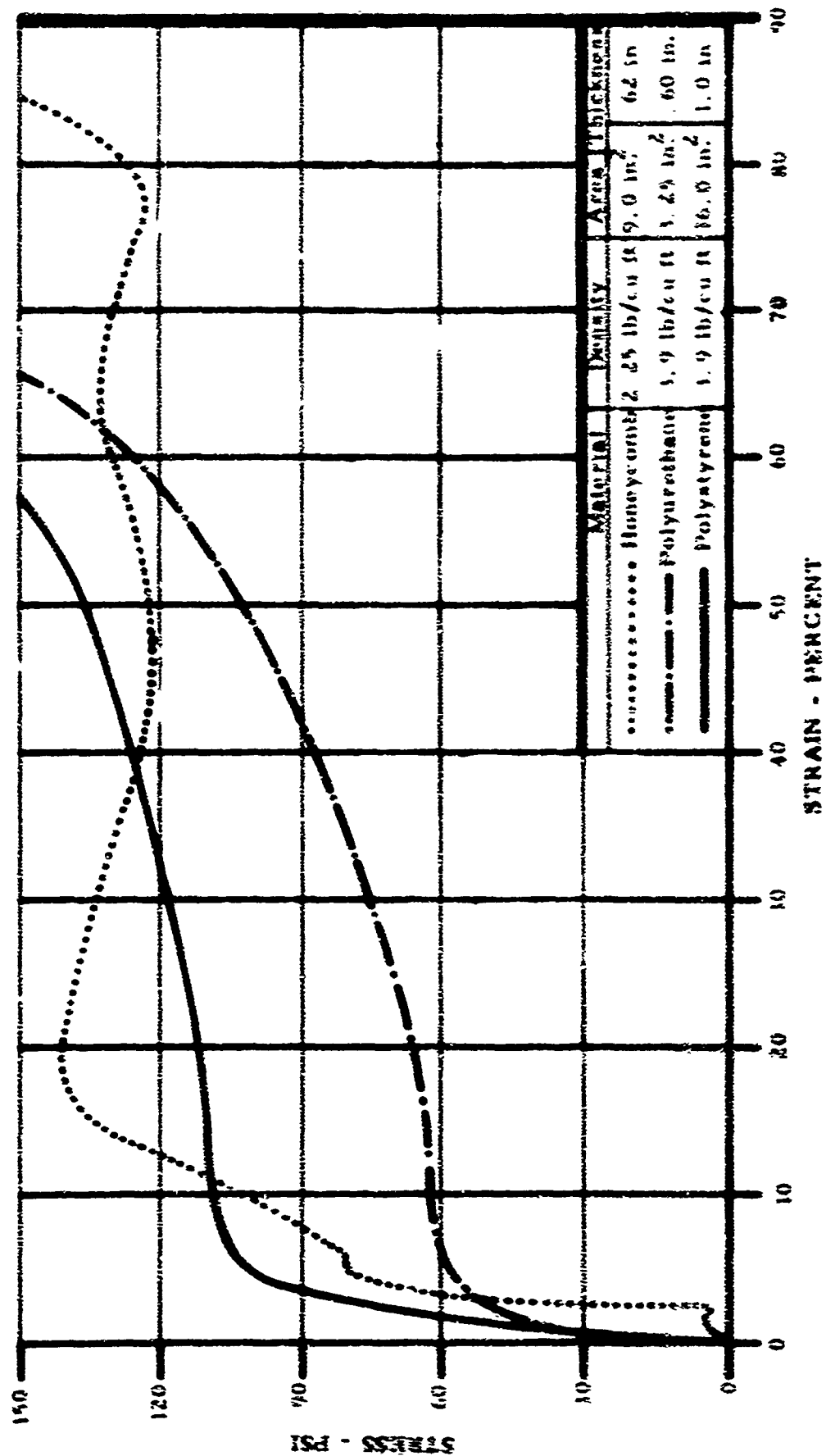


Figure 9. Stress-Strain Curves for Three Energy-Absorbing Materials.

in comparison with the styrene foam indicates that the stress-strain properties of plastic foams are markedly affected by manufacturing techniques; this statement is substantiated by the foam studies conducted in reference 24.

The compressive stress (σ) of the outer liner required to insure that head accelerations do not exceed "G" gravity units is given approximately by the equation

$$\sigma = \frac{WG + K_2 F_s}{K_1 A}$$

σ = maximum stress in the crushed area

where W = weight of the head and helmet combination

F_s = force required to compress the outer shell alone

K_1 = a constant equal to the ratio of σ_{avg} to σ_{max}

K_2 = a constant dependent upon the interaction between the energy absorber and the outer shell

A = area of foam compressed.

The constants K_1 and K_2 depend upon the shape and amount of the indentation of the outer shell, thus upon the shape of the impact surface and the impact velocity. The constant K_2 accounts for the increase in load-carrying capacity of the outer shell when tested alone, as compared with its load-carrying capacity when stiffened in the areas adjacent to the impact by the energy-absorbing material. The constants K_1 and K_2 were not evaluated in this study. It may be more practical to select the desired outer shell and to then establish during the development of a prototype head protective device by actual experiments. A sample calculation is shown to illustrate the equation:

Assume

$$K_1 = 0.4$$

$$K_2 = 1.5$$

$$F_s = 400 \text{ pounds}$$

W = 13.5 pounds

G = 110G

A = 16 square inches (estimate for front impact - flat surface).

Then

$$\sigma_{\max} = \frac{13.5 \times 110 + 1.5 \times 400}{0.4 \times 16}$$

or

$$\sigma_{\max} = 140 \text{ psi.}$$

This should be the stress at the maximum design strain of 50 to 80 percent depending upon the type of material. The representative stress-strain curves shown previously in Figure 9 indicate crushing stresses in this vicinity at 50 to 80 percent strain values.

A honeycomb material can be expected to yield consistent stress-strain data, whereas the plastic foams appear to yield very irregular data unless strict mixing procedures are followed in their manufacture. Precise control of foam density may not be easily attained as evidenced by the fact that the density of the foam in three production APH-5 helmets was 4.6 pounds per cubic foot rather than 3.0 pounds per cubic foot as specified by the U. S. Navy Aircrew Equipment Laboratory Control Drawing 577. Since it is shown in reference 24 that the compressive strength of plastic foams varies with the square of the density, high densities can result in acceleration levels far above the desirable design range (reference Table 2, Supplement II, specimens 21 and 23). The density of plastic foams is thus extremely important in the control of head accelerations, and strict quality control to insure uniform density in production foams is a necessity. Even though the densities of foams are identical, their stress-strain properties may vary widely as can be seen in Figure 9 by the comparison of styrene and urethane foams of equal density with very unequal stress-strain properties.

OUTER SHELL

The outer shell should be a thin, ductile material to allow deformation of the impacting object into the outer liner; however, the shell must not be so thin that inadequate protection is offered against penetration.

A number of materials were considered for the outer shell and some of the more promising are listed in Table 1. This table includes the physical properties which appear to be pertinent for use in the development of a double-shell concept.

TABLE 1
PHYSICAL PROPERTIES - OUTER SHELL MATERIALS

	Tensile Strength (psi $\times 10^3$)	Modulus of Elasticity (psi $\times 10^6$)	Elonga- tion (pct)	Notch Toughness (ft/lb)	Weight (lb/in ³)
1. Aluminum (2024-0)	24	10.6	12	-	0.100
2. Magnesium (AZ-31B-0)	32	6.5	12-19	Charpy 5.0*	0.064
3. Magnesium- lithium(LA-141)	21	6.5	30	-	0.049
4. Steel (300-M)	289	29.4	10	Charpy 22.0	0.287
5. Fiber glass- epoxy	40-55	3.0-4.6	-	IZOD-12-18	0.060
6. Nylon cloth- epoxy	40-120	0.18-0.19	-	IZOD-3-4	0.040
7. ABS Sheet (High Impact)	8-9	0.37 0.40	20-50	IZOD-3-6	0.037
8. Polycarbonate	9-10	0.35	75	IZOD-14.0	0.043
9. Polypropylene	4	0.12-0.18	-	IZOD-1-3	0.033

* F condition instead of 0 condition.

All of the materials in Table 1 were used in the hemispherical test shapes with the exception of steel, polypropylene, and the magnesium-lithium material. Steel was not used because of the fact that its weight is nearly three times that of aluminum and more than four times that of magnesium; therefore, for equivalent weight, the steel shell would be only one-fourth to one-third the thickness of magnesium or aluminum. It appears that a very thin steel shell would be a poor load distributor and penetration resistor. The polypropylene plastic was eliminated in view of the fact that its properties did not appear as good as polycarbonate for the intended use. The magnesium-lithium material was eliminated because of its excessive cost (\$25 per pound in quantity).

IMPACT TESTING OF HEMISPHERICAL SPECIMENS

A helmet should provide protection when impacted upon either flat, cornered, or sharp, jagged surfaces as noted previously therefore, impact tests were conducted on 27 hemispherical specimens for the purpose of determining the best material combinations for use in resisting all three surface types. The primary objective of the impact testing was the selection of suitable materials for use in double-shell helmets; however, one single-shell specimen was tested as a basis of comparison with the double-shell specimens.

DESCRIPTION OF TEST SPECIMENS

An accurate evaluation of helmet materials requires that the specimens have the approximate contour of a helmet shell since flat specimens do not reveal the true interaction between the shell and energy-absorbing liner or the effects of curvature of the helmet and impacting surface. The contours of the front and back portions of the head have approximately a 3-inch radius; thus, a hemispherical shell with a 6-inch inside diameter was used as shown in Figure 10. A total thickness of 1 inch of protective material was used in all specimens. This thickness includes the outer shell, the energy-absorbing outer liner, the inner shell, and the inner liner. The material combinations used in the 27 specimens are itemized in Table I, Supplement II; however, additional details on the chemical composition of the plastic shells and energy-absorbing liners are discussed below.

Outer Shell

Nylon cloth - 24 x 23 cross weave, 6 ounces per square yard, manufactured by Burlington Industries (this cloth was used in all the nylon shell specimens).

Fiber glass cloth - 18 x 18 cross weave, 6 ounces per square yard, manufactured by Goldsmith Company (this cloth was used in all the fiber glass shell specimens).

The nylon and fiber glass cloths were bonded with epoxy resin as follows:

75 - 88% Epoxy No. 6140, Reichold Chemicals Co.

12 - 25% Hardener (Diethylene Triamine), Reichold Chemicals Co.

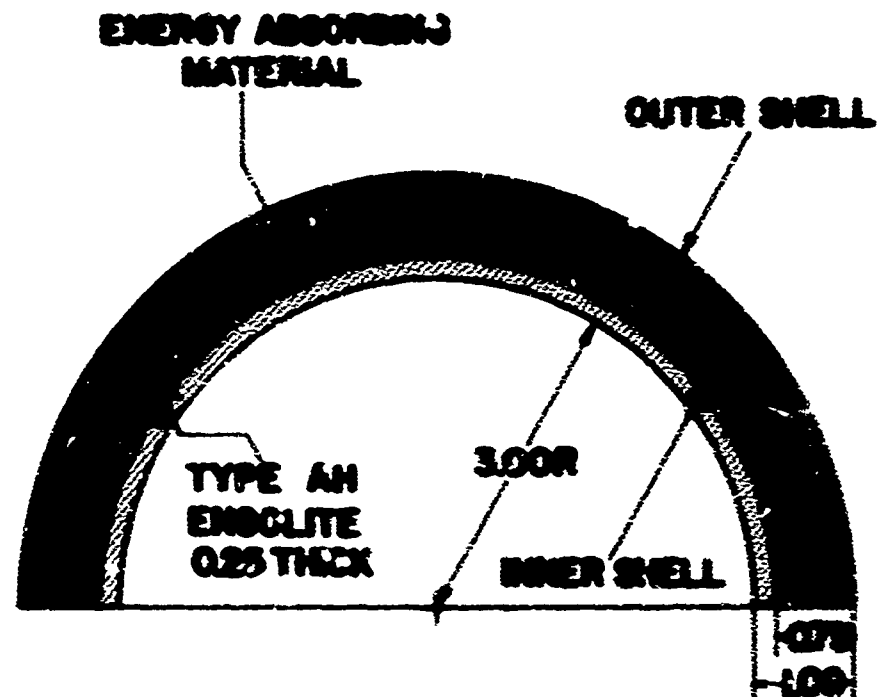


Figure 10. Cross Section of Hemispherical Test Specimen.

Inner Shell

Fiber glass cloth identical to that used on the outer shell was used for all inner shells and it was bonded in the same manner as for the outer shell. The first 13 specimens (numbers 4 through 16) were constructed with 2 plies of fiber glass cloth; however, the remainder of the specimens contained 3 plies of cloth to improve the resistance to penetration and force-distribution capacity.

Outer Liner - (Energy-Absorbing Material)

The following materials were used:

1. Aluminum honeycomb flexcore
2. Polyurethane foam
3. Polyvinyl chloride foam (PVC)

The composition and source of these materials are listed below:

Aluminum Flexcore Outer Liner - Samples of this material were supplied by the Hexcel Company of Inglewood, California. This material has the unique property that it can be readily formed into compound curves. This cannot be done with standard aluminum honeycomb. The cell sizes average 0.33 inch. It is manufactured of 5052 aluminum in a thickness of 0.0013 inch. The flexcore was bonded to the inner and outer shell with the same epoxy used in the lay-up of the cloth shells.

Polyurethane Foam Outer Liner - This material was foamed in place between the inner and outer shells by Western American Plastics, Mesa, Arizona, with one exception: specimen 28 (polycarbonate outer shell) was foamed by Goodyear Aircraft Corporation, Litchfield Park, Arizona. All foaming was done at room temperature to densities varying between 3.1 and 7.0 pounds per cubic foot. The following mixture was used in all specimens:

65 parts No. 8625 Reichold Chemicals Co.
50 parts No. 8605 Reichold Chemicals Co.
1.2 parts water

Polyvinyl Chloride (H-334 Slow-Rebound PVC) Foam Outer Liner - Samples of this material were supplied by the B. F. Goodrich Co., Shelton, Connecticut. This material possesses a rather flat stress-strain curve for a slow-rebound material and retains only a small permanent deformation as shown previously in Figure 5; however, the compressive stress is too low for consideration as the material for the outer liner of a double-shell helmet.

ABS Foam Outer Liner (Sandwiched Royalite) - Samples of this material were supplied by the U. S. Rubber Company, Mishawaka, Indiana. The density of this foam was approximately 11 pounds per cubic foot, which is more than twice the density of polyurethane and polystyrene foams which perform satisfactorily. The high density of this material makes it unattractive for consideration as a helmet liner.

TEST PROCEDURE (Hemispherical Specimens)

The Movable Impact Mass (Impactor) and Fixed Head Form technique as described in Impact Test Methods for Helmets, Supplement I, was used in these tests. The test setup is shown in Figure 11. The steel hemisphere (simulated head) was covered with a 0.25-inch-thick scalp of 10-pound density polyurethane foam as noted previously.

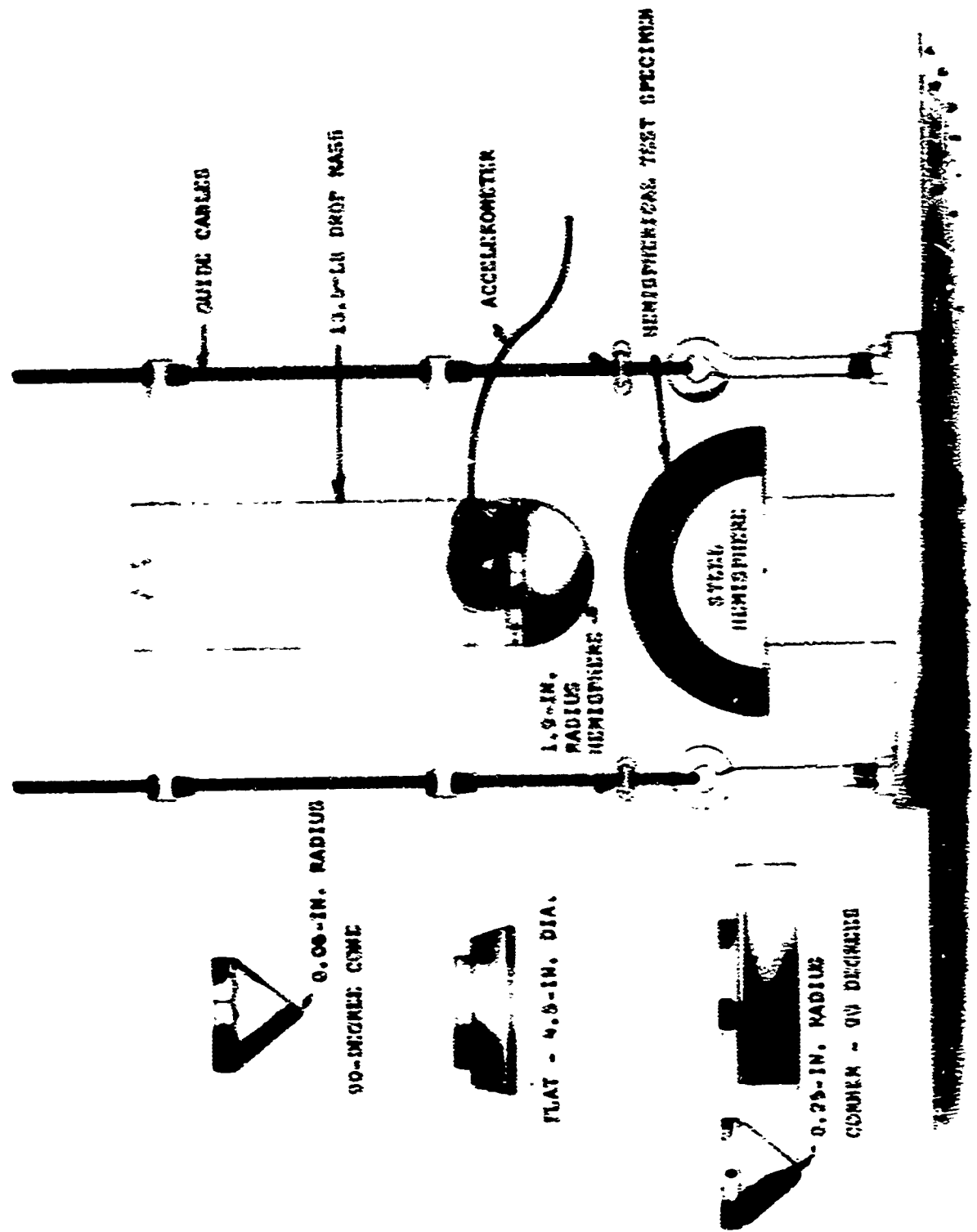


Figure 11. Test Setup for Hemispherical Specimens Showing Different Impactor Surfaces.

Typical indentation in the scalp, caused by some of the cone impactor drops, can be seen in Figure 12.

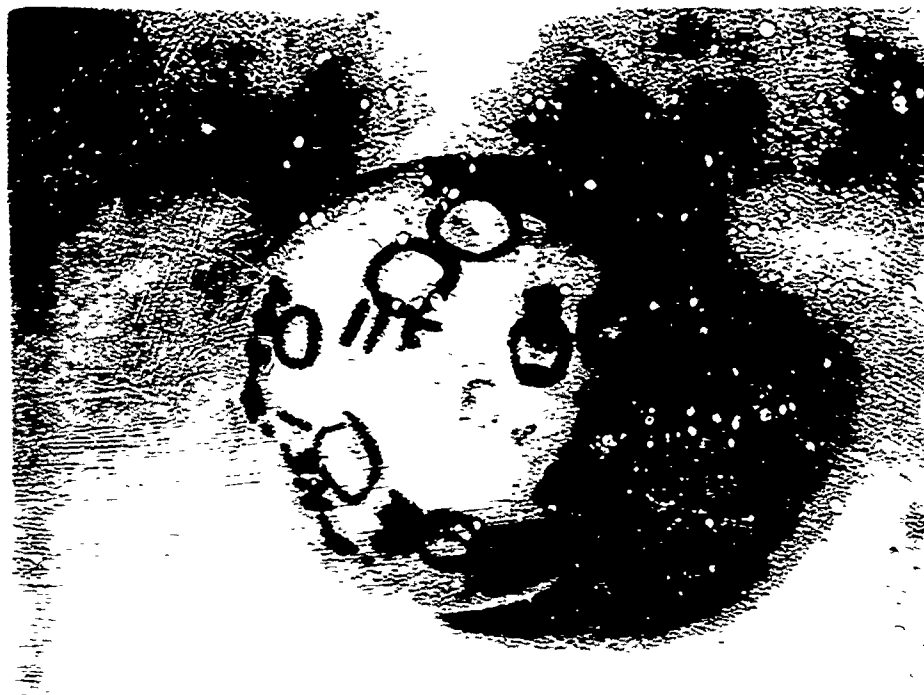


Figure 12. Scalp Indentation Due to Impact Tests With a 90-Degree Cone.

Initial drops with the 90-degree-corner impactor indicated that the 1-inch-thick specimens could absorb the energy of a 4-foot drop (16-feet-per-second impact velocity) without causing any permanent deformation in the polyurethane scalp; therefore, this height was used as a point of departure for all the test specimens and was increased in 1-foot increments until permanent deformation was noted in the scalp. A "standard" drop height of 5 feet for the flat impactors was determined by the same method. The standard drop height of 2 feet for the cone impactor was arbitrarily set at 50 percent of the corner impactor; this test appears to be reasonable to insure a good compromise for protection between the extremes of impact surfaces.

Each hemispherical specimen was impacted in five or more locations, and the impact points were placed far enough apart so that little effect from the damage caused in previous drops would be apparent in subsequent drops. This method of testing has proven to be very economical since a large number of impact sites can be selected on any specimen by simply repositioning the specimen on the steel hemisphere.

The drop weight used was designed so that various types of impactors could be installed as shown in Figure 11. Three types of impact surfaces were used as listed:*

1. Flat surface of 4.5-inch diameter
2. Corner surface of 90 degrees with 0.25-inch radius
3. Cone surface of 90 degrees with 0.06-inch-radius tip.

The impactor (drop mass) was raised to varying heights along guide wires and then released by a solenoid switch. Nylon bushings were used to reduce friction between the impactor and the guide wires. The rebound height of the impactor was estimated by visual observance, and the recorded heights are considered to be correct to within ± 20 percent.

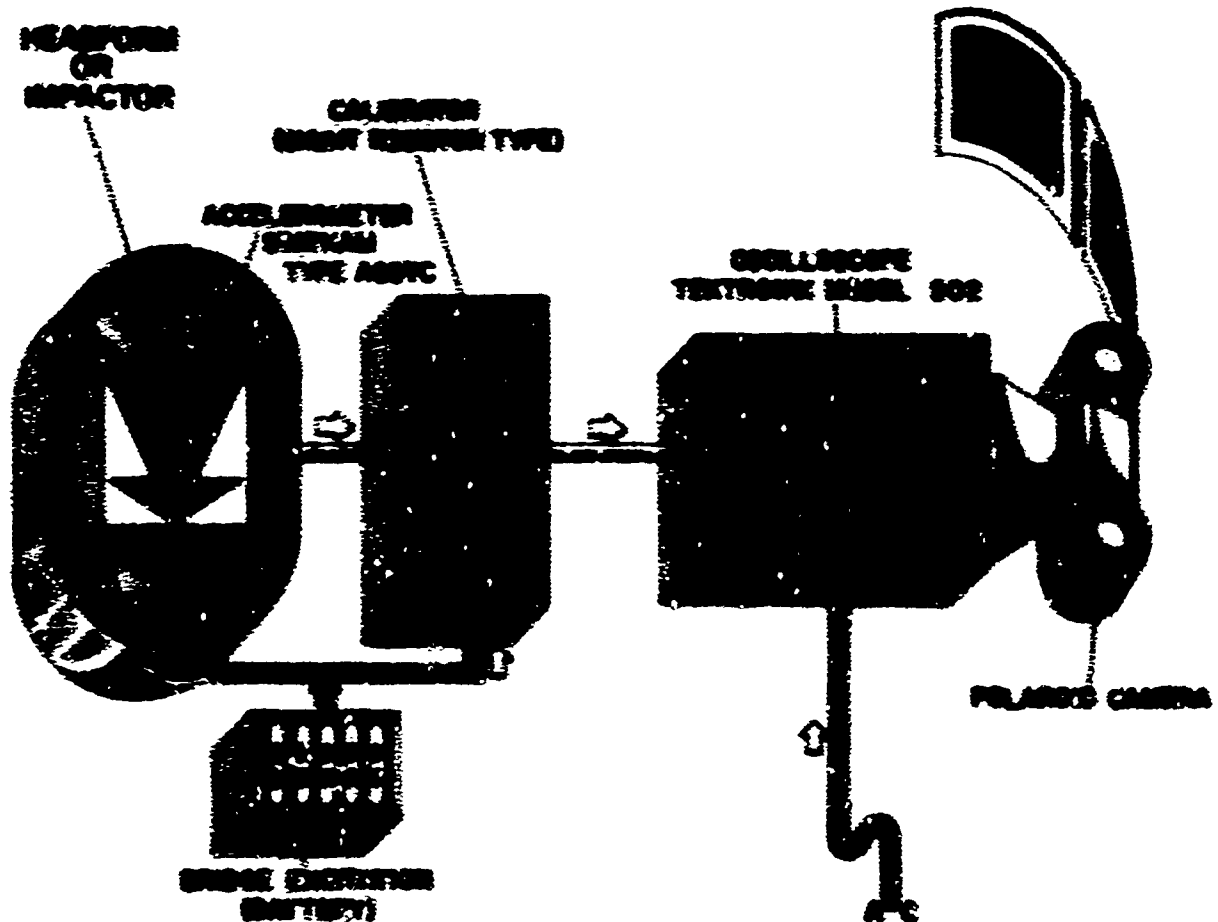


Figure 13. Instrumentation Setup.

* A spherical impactor was constructed but not used in the tests described in this report.

An accelerometer was mounted rigidly inside the impactor as shown in Figures 11 and 13. The specifications for this accelerometer are listed:

Manufacturer-Model	Statham A69TE-500-350
Design Acceleration	+ 500G
Natural Frequency	3800 cycles per second
Guaranteed Frequency Response	2500 cycles per second
Weight	3 ounces

TEST RESULTS - HEMISPHERICAL SPECIMENS

The complete results of the impact tests on the 27 hemispherical specimens are recorded in tabular and graphical form in Supplement II. Typical results are presented in this section for four of the specimens which were representative of the complete group and which illustrate both good and fair performance. The four specimens were constructed of the material combinations shown in Table 2, and are referred to in the following discussion by the specimen numbers (15, 17, 21 and 27) as given in the left hand column of the table.

TABLE 2
HEMISPHERICAL TEST SPECIMEN MATERIALS

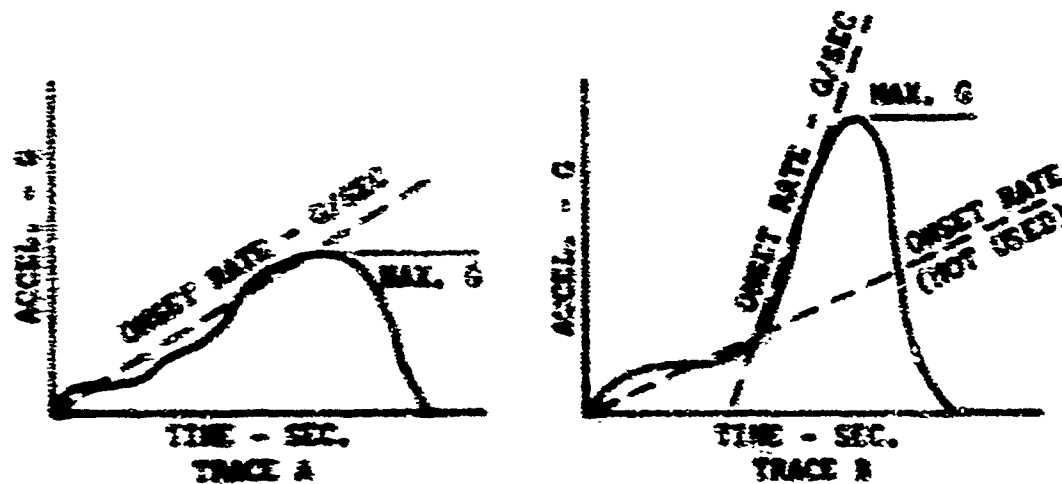
Spec. No.	Outer Shell Material	Outer Shell Thickness (in)	E/A* Outer Liner Material	E/A* Material Density (lb/ft ³)	Inner Shell Material	Inner Liner Material	Total Weight (lb)
15	Nylon-epoxy 8-ply	0.10	Poly-urethane Foam	4.0	Fiber glass epoxy-3-ply	Encolite Type AH	0.71
17	Fiber glass epoxy 8-ply	0.08	↓	4.0	NONE	↓	0.57
21	AZ-31B Mag. (annealed)	0.040		6.0	Fiber glass epoxy-3-ply		0.64
27	ABS	0.08	Poly-urethane Foam	3.7	Fiber glass epoxy-3-ply	Encolite Type AH	0.54

* Energy-Absorbing

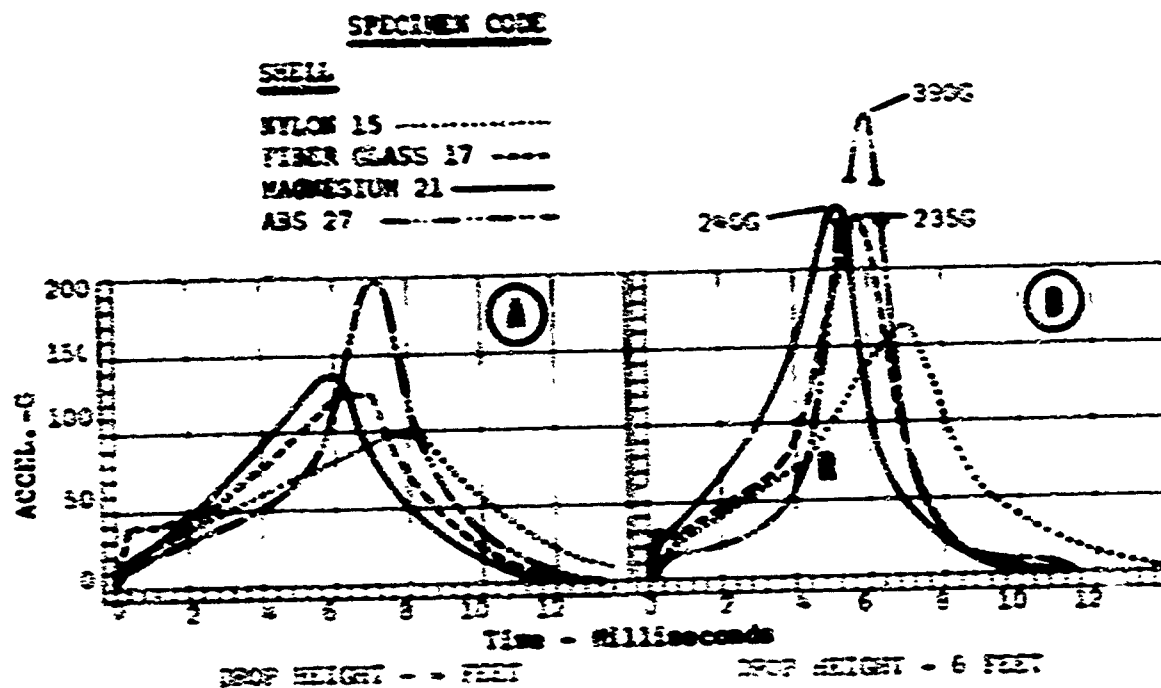
As shown previously in Figure 10, the total thickness of each specimen was 1.00 inch and the inner liner was 0.25 inch thick. Thus, about 5/8-inch thickness of energy-absorbing material was used compared with about 1 inch of energy-absorbing material in the frontal area of the experimental helmets described later in this report.

The acceleration-time traces for these four specimens are compared in Figure 14. This figure includes the significant data for the 90-degree-corner surface and flat surface impacts. The acceleration values for the cone impacts are presented only in Supplement II, because the accelerations recorded in the cone tests are lower than those recorded in the corner and flat-surface tests for those cases in which bottoming or complete penetration of the specimen does not occur. Thus, with the exception of identifying penetration, the shape of the acceleration-time trace is less important for the cone tests.

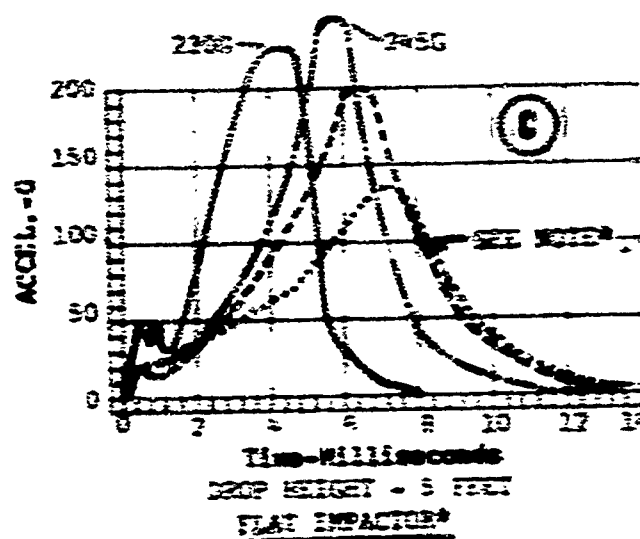
Table 3 is presented as an extract of Supplement II and is appropriately described in the discussion below to explain the additional data available in the Supplement. The values in this table are based upon acceleration-time traces which fit the general shape of one of those shown in the sketch below.



The onset rate given in Table 3 is the greater of the rates shown in traces A & B. The high onset rates are associated with the permanent depressions in the skull cap. This table also includes the peak acceleration and the rebound height of the impactor for each drop. The rebound height is indicative of the elastic energy stored in the specimen after impact. The performance of the four selected specimens is presented by specimen number.



90-DEGREE-CORNER IMPACTOR



90-Degree-Corner Impactor Used Instead of Flat Impactor on Specimen 15.

Figure 14. Acceleration-Time Data - Specimens 15, 17, 21, and 27.

TABLE 3
TEST RESULTS OF SELECTED HEMISPHERICAL SPECIMENS

Test Conditions:

1. Impactor Weight - 15.5 lb.
2. Total Specimen Thickness - 1.0 inch
3. See Table 2 for complete description of specimens.

Specimen Identity #	IMPACTORS - 90° CONE				90° CORNER			FLAT	
	DROP HT.				4 ft.	5 ft.	6 ft.	5 ft.	6 ft.
No. 15	Onset rate (ft/sec)	2 ft.	4 ft.	5 ft.	13,000	26,000	16,000	26,000	-
	Max. Accel. (G)	-	150	-	95	110	160	115	-
	Rebound Ht. (ft.)	-	-	0.1	0.9	0.9	0.7	0.8	-
	Footnotes	-	-	-	-	b	c	a, d	-
No. 17	Onset rate	5,000	-	-	26,000	52,000	70,000	60,000	-
	Max. Accel.	55	-	-	120	160	215	230	-
	Rebound Ht.	0.1	-	-	0.5	0.8	0.9	0.9	-
	Footnotes	a	-	-	b	c	c	-	-
No. 21	Onset rate	8,000	14,000	-	26,000	50,000	86,000	91,000	107,000
	Max. Accel.	55	95	-	115	175	240	210	265
	Rebound Ht.	0.2	0.1	-	0.4	0.5	0.6	0.5	0.6
	Footnotes	-	b	-	-	-	a	-	-
No. 27	Onset rate	11,000	-	-	95,000	-	220,000	100,000	400,000
	Max. Accel.	65	-	-	200	-	190	505	440
	Rebound Ht.	0.1	-	-	0.4	-	0.6	0.8	0.8
	Footnotes	b	-	-	a	-	c	-	a

Footnotes:

- a - Slight permanent depression of 0.04 inch depth and 0.3 square inch area or less in simulated scalp
- b - Moderate permanent depression of 0.04-0.10 inch depth and up to 0.4 square inch area in simulated scalp
- c - Severe permanent depression of 0.10 inch depth and 0.4 square inch area or more in simulated scalp
- d - 90-degree-corner impactor used instead of flat impactor

Specimen 15

As shown in Table 2, this specimen contains a nylon-epoxy, 8-ply outer shell of 0.10-inch thickness, an energy-absorbing polyurethane outer liner of 4.0-pounds-per-cubic-foot density, and an inner shell of 2-ply fiber glass. The inner liner was 1/4-inch-thick type AH Ensolite, which material was used in all four specimens. Specimen 15 weighed 0.71 pound as shown in Table 2.

Figure 14A shows that an acceleration level of just under 100G (dotted curve) was sustained in the 4-foot drop of the corner impactor; furthermore, Figure 14B shows that the maximum acceleration increases to 160G for a 6-foot drop with the same impactor. The change in slope of the curve at point R shows that the energy-absorbing material is becoming compacted and that a bottoming tendency is starting although bottoming is not yet extremely severe. Higher velocity drops progressively increase the peak acceleration as bottoming becomes more severe.

Table 3 shows that specimen 15 had good resistance to a 4-foot cone impact also. A 150G acceleration level was reached although there was no evidence of penetration into the simulated scalp.

The reader should be cautioned against concluding from an observation of the acceleration-time curves of Figure 14, that specimen 15 would yield the best performance in a helmet. While it did unquestionably perform well, its weight was 0.71 pound compared with specimen 21 at 0.64 pound as shown in Table 2. Also, specimen 21 had an energy-absorbing liner of 6.0-pounds-per-cubic-foot density, which, if reduced, would (a) further reduce the overall specimen weight and (b) reduce the maximum accelerations to values corresponding to those recorded for specimen 15. The rebound energy (see rebound height recorded for the various drops in Table 3) for specimen 15 was also slightly higher than for specimen number 21, and the rebound height of specimen 21 would undoubtedly be lower if its density were reduced as can be gleaned from a review of the data on the experimental helmets in Table 4 in which the drop height was 7 feet instead of 4 feet and the rebound height was slightly less.

Specimen 17

Specimen 17 had an 8-ply fiber glass epoxy outer shell and it was similar to specimen 15 except that no inner shell was used. The acceleration level for the 4-foot, 90-degree-corner impactor was 120G as shown in Figure 14A. It is noted in Table 3, however, that a permanent deformation was recorded in the simulated scalp which is indicative of inadequate load distribution in this specimen. The reserve capacity of this specimen, as indicated by the 6-foot, 90-degree-corner drop, was poor as shown by the 235G peak acceleration recorded (Figure 14B). The 5-foot drop with a flat impactor resulted in a 200G acceleration level which would be unacceptable for a helmet. The specimen did not indicate good resistance to a 2-foot cone impact since a slight permanent depression in the simulated skull was noted as recorded in Table 3. This performance against the cone impact is in marked contrast to specimen 15 which did not indicate any penetration even in a 4-foot drop. The rebound energy for this specimen was very little different from that of specimen 15 as may be observed by comparing the rebound heights as recorded in Table 3.

Specimen 21

This specimen had an 0.04-inch-thick magnesium outer shell, but it was similar to specimen 15 in other respects. The acceleration level for this specimen for the 4-foot, 90-degree-corner impact was 135G. This is high in accordance with the values previously noted in the human tolerance section of this report, if a 3.25 factor of safety based on fracture is to be used. This high acceleration was caused by the high-density (6 pounds per cubic foot) foam used in the energy-absorbing liner. It is shown in the "Impact Testing of Experiment Helmets" section of this report that a helmet constructed in the same manner as specimen 21, but with 3.2-pounds-per-cubic-foot density, energy-absorbing material, yielded an acceleration of only 85G for a 4-foot drop with a 90-degree-corner impactor (reference Table 8, drop number 33G). Specimen 21 also gave an excessive acceleration of 240G for the 6-foot corner impactor drop. The 5-foot drop with a flat impactor gave an acceleration of 230G although no permanent deformation was noted in the simulated scalp for this drop. A cone drop from 2 feet did not result in permanent deformation of simulated scalp, while a drop of 3 feet did result in permanent depression as noted in Table 3. The resistance against the cone impactor was not as good as that for specimen 15; however, the performance is considered adequate in view of the fact that it protects 40 to 50 percent of the energy level for a corner impactor.

The rebound recorded for this specimen (0.6 foot for 6-foot drop of 90-degree-corner impactor) is the lowest of the four specimens discussed here. Reference to Table 8 reveals that helmet 33 (3.2 pounds-per-cubic-foot density) yielded rebound heights of about half of those heights recorded for specimen 21 in Table 3. The annealed metal shells tend to remain permanently deformed, while the plastic shells tend to regain their shapes after impact. The permanent deformation remaining in the metal shell specimens, therefore, is indicative of good energy absorption without excessive rebound energy.

Specimen 27

This specimen was constructed with an 0.08-inch-thick, ABS plastic, outer shell. The energy-absorbing liner of urethane foam had a density of 3.7 pounds per cubic foot. The acceleration level for the 4-foot, 90-degree-corner impactor was 200G, an excessive value, and a permanent depression was noted in the simulated scalp as shown in Table 3. The 6-foot-corner impactor drop resulted in a 390G acceleration with a severe permanent depression in the simulated scalp of more than 0.10 inch. The flat impactor resulted in a 245G acceleration level which is also excessive in accordance with the values noted in Figure 5. This specimen also indicated very poor performance in the 2-foot cone impact since a permanent depression was noted in the simulated scalp for this drop. This specimen was also found to store relatively large amounts of elastic energy in flat surface impacts as reflected in the 0.8 to 1.0 foot rebound heights given in Table 3 for the 5-foot and 6-foot drops.

The tests conducted on the 27 specimens reveal generally that (1) specimens constructed with magnesium outer shells performed satisfactorily and weigh less than other specimens, (2) the annealed aluminum and magnesium shells yield lower rebound velocities than other outer shell materials, (3) the density of foamed-in-place polyurethane liners should not exceed 4 pounds per cubic foot in order that head tolerance limits are not exceeded in flat impacts, and (4) highly ductile plastic shells, such as ABS and polycarbonate, do not perform as well as the other shells tested.

IMPACT TESTING OF EXPERIMENTAL HELMETS

Impact tests were conducted on two experimental helmets and on one of the 9-ply nylon shell helmets developed by the Natick Engineering and Research Center. Two methods of testing were employed: (1) the impactor mass was dropped onto a stationary helmet head form, and (2) the helmet head form was dropped as a unit onto the impact surface.

DESCRIPTION OF EXPERIMENTAL HELMETS

As already noted, satisfactory helmets can be assembled from many combinations of shells and energy-absorbing materials as long as the requirements with respect to head deceleration level and resistance to penetration are met. The experimental helmet, which was constructed to demonstrate the concepts discussed in this report, was made up of the following major components:

1. Outer shell, 0.040-inch annealed magnesium (AZ-31B-0)
2. Outer liner, 3.0 to 5.0 pounds per cubic foot, foamed-in-place polyurethane
3. Inner shell, 4-ply fiber glass (6 ounces per square yard)
4. Inner liner, PVC slow-rebound foam, 4-pounds-per-cubic-foot density
5. Suspension, crocheted nylon net* (3/16-inch openings, adjustable by drawstrings)
6. Retention harness, crocheted nylon net* (3/16-inch openings with 1/16-inch by 1-inch nylon chin strap)
7. Earmuffs, noise attenuating type, manufactured by Carter Engineering Co., Los Angeles, California.

The above elements of the experimental helmet are illustrated in Figure 15, and photographs of the helmet are shown in Figures 16 and 17.

* Net material identified as Imperial Nylon Net, Manufactured by Davis Mills, Inc., Lake City, Tenn

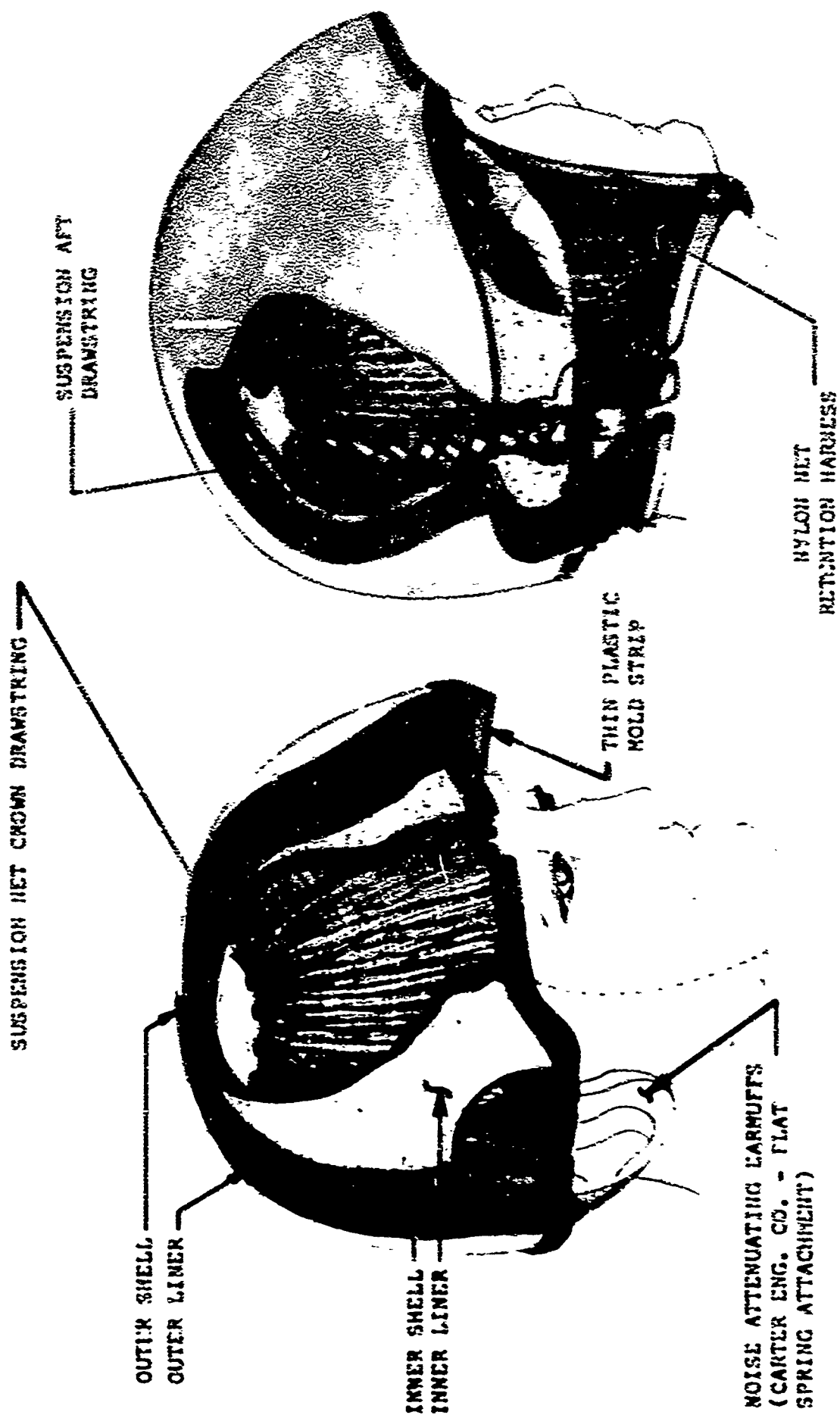


Figure 15. Cutaway View of Experimental Helmet.



**Figure 16. Three-Quarter Front View of Experimental Helmet
Showing Nylon Net Suspension and Retention Harness.**

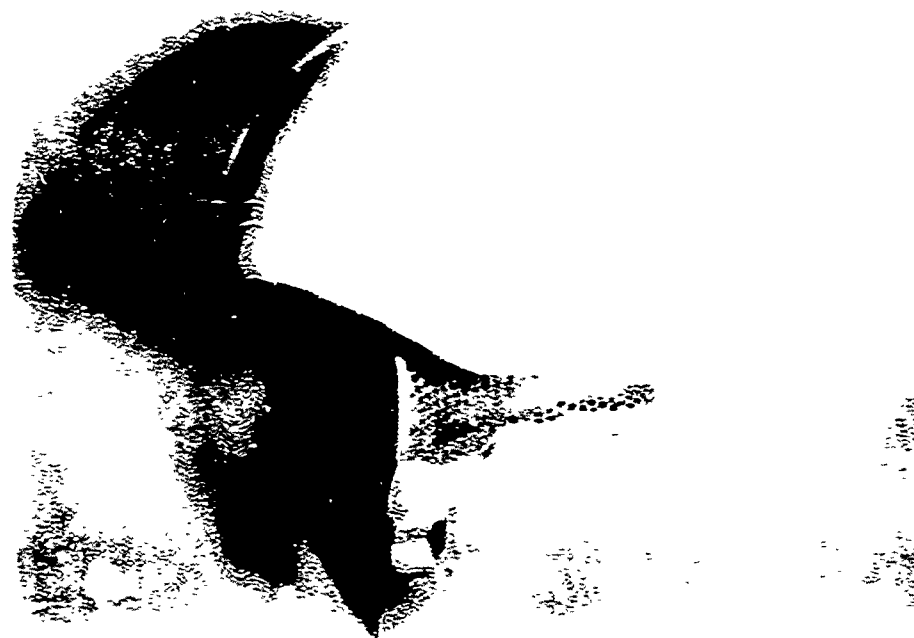


Figure 17 Profile View of Experimental Helmet.

The weight breakdown of the experimental helmets which were tested is shown in Table 4.

TABLE 4
EXPERIMENTAL HELMET WEIGHTS - 95-PERCENTILE SIZE

	Helmet No. 32 (lb)	Helmet No. 33 (lb)
Outer Shell - 0.040 Magnesium	0.51	0.50
Outer Liner - Polyurethane foam	0.45*	0.27**
Inner Shell - 4-ply fiber glass	0.60	0.45
Inner Liner - Polyvinyl chloride foam (PVC)	0.12	0.21
Suspension and Retention Harness Nylon net	0.16	0.16
Total	1.87	1.59

* Foam density = 5.7 pounds per cubic foot

** Foam density = 3.2 pounds per cubic foot

The weight breakdown of the 9-ply nylon helmet supplied by the Natick Engineering and Research Laboratory is shown in Table 5.

TABLE 5
NYLON HELMET WEIGHTS - 90-PERCENTILE SIZE

	Helmet No. 36 (lb)
Outer Shell and Energy-Absorbing Liner	2.19
Fitting Pads	0.12
Retention Harness	0.14
Total	2.45

The above weights do not include a visor, visor support hardware, or communications equipment.

The experimental helmets had a total thickness of about 1.35 inches in the frontal area; however, the thickness tapered to the values given in Table 8 in other areas. Four experimental helmets which will fit up to a 95-percentile head were constructed in this study; these helmets are numbered and identified in Table 6.

The weight breakdown of the experimental helmets which were tested is shown in Table 4.

TABLE 4
EXPERIMENTAL HELMET WEIGHTS - 95-PERCENTILE SIZE

	Helmet No. 32 (lb)	Helmet No. 33 (lb)
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Inner Liner - Polyvinyl chloride foam (PVC)	0.12	0.21
Suspension and Retention Harness Nylon net	0.16	0.16
Total	1.87	1.59

* Foam density = 5.7 pounds per cubic foot

** Foam density = 3.2 pounds per cubic foot

The weight breakdown of the 9-ply nylon helmet supplied by the Natick Engineering and Research Laboratory is shown in Table 5.

TABLE 5
NYLON HELMET WEIGHTS - 80-PERCENTILE SIZE

	Helmet No. 36 (lb)
Outer Shell and Energy-Absorbing Liner	2.19
Fitting Pads	0.12
Retention Harness	0.14
Total	2.45

The above weights do not include a visor, visor support hardware, or communications equipment.

The experimental helmets had a total thickness of about 1.35 inches in the frontal area; however, the thickness tapered to the values given in Table 8 in other areas. Four experimental helmets which will fit up to a 95-percentile head were constructed in this study; these helmets are numbered and identified in Table 6.

TABLE 6
EXPERIMENTAL HELMET IDENTITY - 95TH PERCENTILE SIZE

Helmet No.	Vent Holes	End Use	Total Weight* (lb)
X-32	Yes	Test	1.87
X-33	Yes	Test	1.59
X-34	No	Demonstration	2.00
X-35	Yes	Demonstration	1.80

* Weight includes suspension and retention harness but does not include earmuffs and earphones.

TEST PROCEDURE

The tests were conducted by two methods. In the first method, the same impactor used for the hemispherical specimens, as shown in Figure 11, was used to impact the rigidly mounted helmet head form assembly. In the second method, the impactor was rigidly mounted and the instrumented helmet head form combination was dropped onto it as shown in Figure 18.

A 50-percentile head form was cast of magnesium, with provisions for mounting the accelerometer at the center of gravity of the helmet head form drop jig assembly.

The accelerometer mounting in the head form was so designed that it could be positioned to align with the anticipated acceleration vector for a complete range of head-helmet positions. A photograph of the disassembled head form and accelerometer is shown in Figure 19.

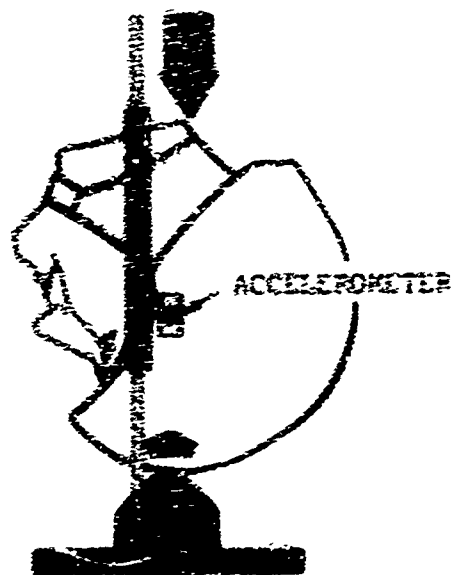


Figure 18. Test Method Using Droppable Head Form.



Figure 19. Accelerometer installation in Droppable Head Form.

The weight of the helmet head form droppable mass is shown in Table 7.

TABLE 7
WEIGHT OF HELMET AND HEAD FORM (DROP WEIGHT)

Item	Helmet Identity		
	No. X-32 Exp. (lb)	No. X-33 Exp. (lb)	No. 36 Nylon (lb)
Head form	9.46	9.46	9.46
Accelerometer	1.04	1.04	1.04
Mounting			
Drop Jig	0.50	0.50	0.50
Helmet (includes ear- phones and muffs)	2.00	1.72	2.90
Total Drop Weight	13.00	12.72	13.90

The same data retrieval system used with the hemispherical specimens, as illustrated in Figure 13, was also used in these tests.

The location of impacts on the helmets and the types of impactors used are shown in Figure 20.

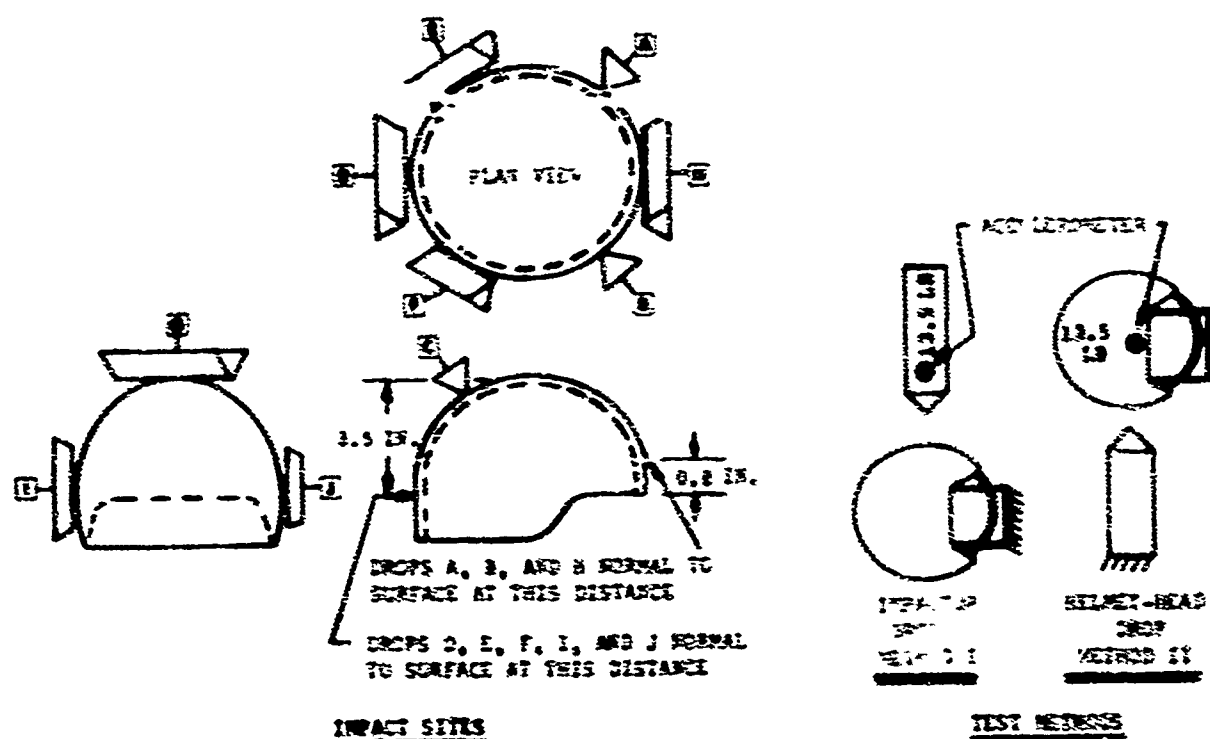


Figure 20. Location of Impacts and Test Methods Used for Testing Helmets.

TABLE 8A
TEST RESULTS - EXPERIMENTAL HELMETS*
 (Total Droppable Weight - approx. 13 5 lb)

IMPACT SURFACE →		30-DEGREE CONE (0.95 In. Radius)			FLAT (4.5 In. Dia.)	
IMPACT SITES →		A	B	C	I	J
DROP HEIGHTS →		4 ft	4 ft	3 ft	5 ft	5 ft
TEST METHOD →		I	II	I	I	II
Helmet Identity ↓	Measured Data ↓					
No. X-32	Thickness-In.	-	1.2*	1.00	b	b
0.04 Mag.	Onset Rate-G/sec	-	30,000	10,000	30,000	65,000
5.7 lb/ft ³	Max Accel-G	-	65	42	140	170
Foam	Rebound Ht.-ft	-	0.1	0.2'	0.4'	0.2'
	Footnotes	-	-	a	-	-
No. X-33	Thickness-In.	1.25	1.25	0.95	b	b
0.04 Mag.	Onset Rate-G/sec	4,000	15,000	30,000	12,000	30,000
3.2 lb/ft ³	Max Accel-G	60	95	120	85	130
Foam	Rebound Ht.-ft	0.2'	0.1'	0.2'	0.2'	0.2'
	Footnotes	-	-	a,d	-	-
No. 35	Thickness-In.	0.80	0.83	0.60	c	c
9 Ply Nylon	Onset Rate-G/sec	12,000	35,000	8,000	60,000	105,000
No Inner	Max Accel-G	90	150	60	150	210
Shell 4.6	Rebound Ht.-ft	0.3'	0.3'	0.4'	0.4'	0.4'
lb/ft ³ Foam	Footnotes	-	-	-	-	-

a. The cone penetrated the inner liner; however, it did not contact the magnesium head form.

b. Thickness varied in this area (due to recessing for earphones) from 0.4 inch at helmet lower edge up to 1.3 inches in the upper area. An earphone and earmuff (as described in Test Specimen Description) were installed.

c. The only energy-absorbing material in this area (except at the upper edge of the earphone cut outs) is the nylon outer shell and the standard military earmuffs and earphones (MX 2000/U).

d. These impacts were placed within 1 inch of the 1-inch-diameter vent holes.

* See Figure 20 for explanation of Impact Sites and Test Method. See "Test Results - Hemispherical Specimens" for definition of Onset Rate.

TABLE 8B
TEST RESULTS - EXPERIMENTAL HELMETS (CONT'D.)
 (Total Droppable Weight - approx. 13.5 lb)

IMPACT SURFACE →		92-HELMET CORNER (0.25-IN. RADIUS)				
		D	E	F	G	H
IMPACT SITES →						
DROP HEIGHT →		3 ft	3 ft	3 ft ^a	5 ft	7 ft
TEST METHOD →		I	I	II	I	I
Helmet Identity ↓	Measured Data ↓					
No. X-32 0.04 Mag. Shell 5.7-lb. Foam	Thickness-in.	0.80	0.80	0.81	1.10	1.33
	Crash Rate-G/sec	-	-	35,000	25,000	15,000
	Max. Accel.-G	200	100	100	100	150
	Rebound Ht.-ft.	0.3'	0.4'	0.4'	0.4'	0.7'
	Footcandles	-	-	-	-	-
No. X-33 0.04 Mag. Shell 3.2-lb. Foam	Thickness-in.	0.80	0.80	0.83	1.10	1.36
	Crash Rate-G/sec	12,000	-	2,500	12,000	100,000
	Max. Accel.-G	300	200	45	25	700
	Rebound Ht.-ft.	0.3'	0.4'	0.3'	0.4'	0.3'
	Footcandles	-	-	-	-	-
No. 36 9-Fly Nylon No Inner Shell 6.6-lb. Foam	Thickness-in.	0.76	0.83	0.83	0.83	0.81
	Crash Rate-G/sec	12,000	12,000	-	55,000	155,000
	Max. Accel.-G	100	70	-	115	150
	Rebound Ht.-ft.	0.4'	0.4'	0.4'	0.3'	0.3'
	Footcandles	-	-	-	-	-

- Helmet 32 was dropped from 5 feet rather than 3 feet.
- These approximate values were read from oscilloscope; no trace was obtained.
- The peak acceleration value exceeded the 100G range set on the oscilloscope.

The tests were conducted in sequence in accordance with the alphabetical listing from A through J in order that the damage imposed by each impact would least affect the subsequent impacts; that is, tests A, B, and C were cone drops which resulted in localized damage, while tests D, E, F, G, and H were 90-degree-corner drops, and tests I and J were flat surface drops, which resulted in the largest area of damage.

TEST RESULTS

The test results are presented in numerical form in Table 8 and in graphical form in Figures 21 and 22. The test conditions, test method, and impact locations are noted in the previous section. Table 8 includes helmet thickness,* the acceleration onset rate, the maximum (peak) acceleration, and the rebound height. The acceleration-time traces for the 90-degree-corner drops from 4 feet and 7 feet and the flat surface impacts from 5 feet are compared in Figures 21 and 22.

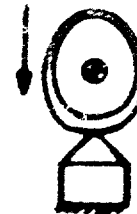
No duplicate tests were conducted because of the limited number of specimens available. Although many tests should be conducted in order to establish statistically significant results, the following general observations should be valid.

Reference to the column headed 90° Cone in Table 8 shows that all three helmets have good resistance to the 4-foot cone impacts in the frontal areas, although 150G was recorded for the 9-ply nylon helmet using the movable head helmet test method (Impact Site B). The double-shell helmets (Nos. 32 and 33) gave accelerations of 65G and 95G respectively. Helmet No. 32 with the higher density foam gave the lower acceleration value (65G) indicating that some bottoming was occurring in the test of specimen No. 33; however, no penetration of the inner shell of specimen No. 33 occurred. It should be noted that the impact velocity in these tests was 16 feet per second and that the impact energy was approximately 4 feet times 13.5 pounds = 54 foot-pounds. This would be equivalent to about 100 foot-pounds in tests in which a movable head helmet assembly is impacted by an equal mass. With the exception of the 150G recorded for the nylon helmet (No. 36), the acceleration levels were quite acceptable.

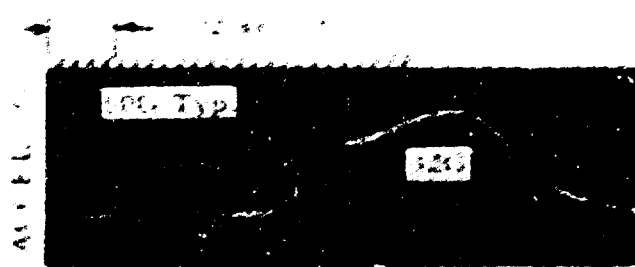
* The "helmet thickness" noted in Table 8 is the thickness of the outer shell, urethane foam liner, and the inner fiber glass shell for the X-32 and X-33 helmets, while the thickness includes only the outer shell and liner for No. 36 helmet since no inner shell was used.



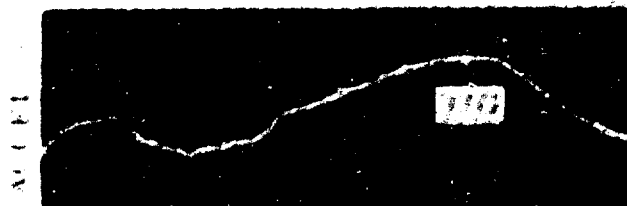
90-DEGREE CORNER SURFACE



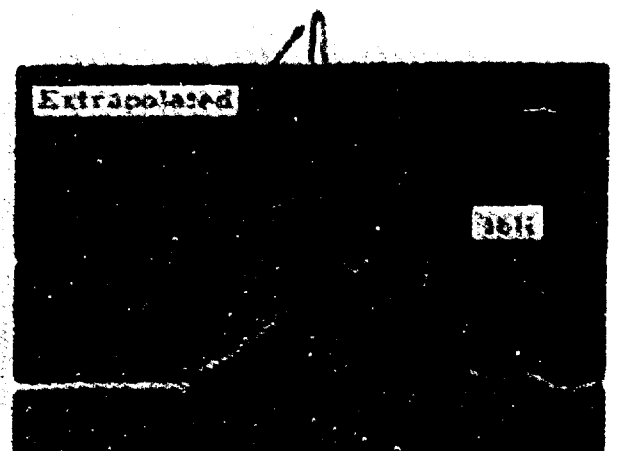
90-DEGREE
TANGENTIAL IMPACT



Nylon Shell and Fiber Glass Inner Shell
With Form Liner



Nylon Shell and Fiber Glass Inner Shell
With Form Liner



Nylon Shell with No Inner Shell

4.145 - 2000

1.000 - 1000

Figure 21 Acceleration-Time Data Comparison of Magnesium and Nylon Shell Helmets for Impacts from a 90-Degree-Corner Surface

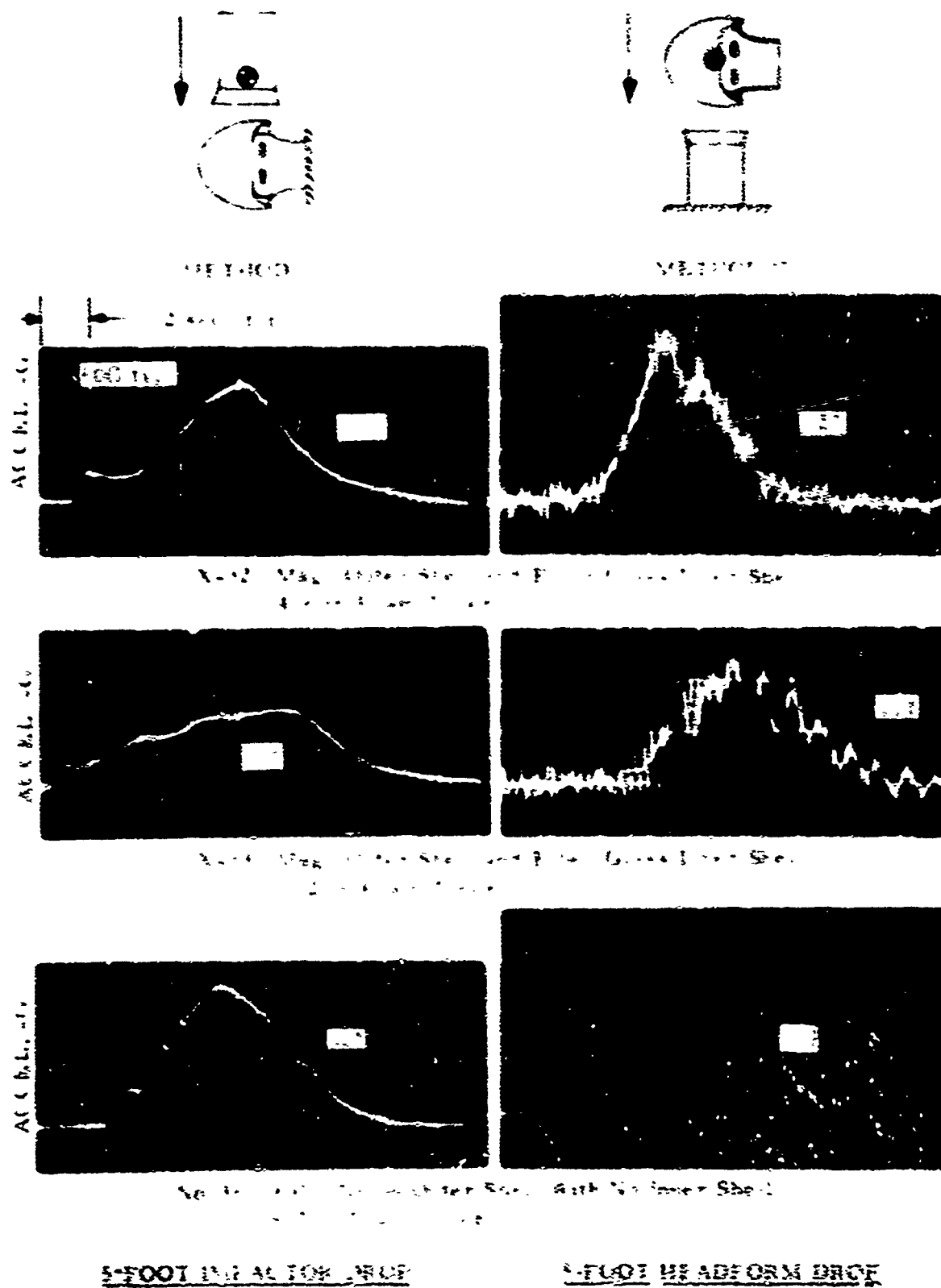


Figure 22 Acceleration-Time Data Comparison of Magnesium and Nylon Shell Helmets for Impacts on a Flat Surface.

All three helmets indicated adequate resistance to the 90-degree-corner impacts in the aft (occipital) and crown regions (impact sites D, E, F, and G) for 3-foot and 4-foot drops, with one exception: Specimen 33 at impact site D (center occipital) revealed bottoming with a peak reading of 205G. This drop was obviously just above the energy-absorption capacity at this point since no bottoming occurred at sites E and F to either side in subsequent drops on the same specimen.

Figure 21 allows a comparison of the nature of the acceleration-time records for 4-foot and 7-foot drops on the three helmets. The sharp peaks appearing in the records for the 7-foot drops show that bottoming is occurring and that the effective energy-absorption capacity has been exceeded. Impacts at still higher velocity will further increase these peak accelerations. Note that the 9-ply nylon helmet gave a 300+G peak for the 7-foot drop compared with 150G for the double-shell helmet No. 32. The 150G deceleration for this specimen is near the threshold of decelerative limits as discussed earlier.

The best performance against the side, flat impact from 5 feet was exhibited by the low density foam helmet No. 33. This would be anticipated since the flat impact compresses a large area of energy-absorbing material. Helmet No. 36 again produced high, although probably survivable, acceleration levels.

Figure 22 illustrates that the 5-foot flat impacts by the impactor drop (Method I) gave consistently lower acceleration levels than for the corresponding drop of the head helmet assembly onto a fixed anvil (Method II). An exception to this trend was noted with the 90-degree-corner impacts from 3 feet on helmet No. 33 in which a higher acceleration value was noted for the impactor drops (No. 33D and 33E) than for the head form drop (No. 33F). It should be noted that impactor drop No. 33D resulted in bottoming with a maximum acceleration of 205G; therefore, this value is not comparable with drop 33E in which only 65G was recorded. The difference in drops 33E and 33F may be due to localized variation in the density of the foamed energy-absorbing material; however, further testing is needed to correlate the two methods.

The above results lead to the following conclusions:

1. The double-shell helmet concept shows good performance for a wide range of impact conditions from the cone to the flat impact.
2. If polyurethane foam of the type and thickness employed in these tests is to be used, the density should be between 3 and 4 pounds

per cubic foot, and probably close to the lower value. Actually, it is the stress-strain characteristics of the material which are important and not the material density.

3. The impact capabilities of the double-shell helmets described here greatly exceed the requirements as listed in MIL-H-22995. These helmets are about equal in weight to the APH-5 and APH-6 helmets in current use, and they are about 3/4 pound lighter than the 9-ply nylon helmet proposed as a replacement for the APH-5.
4. All of the acceleration levels recorded in the tests of these three helmets, including Test No. 36H on the 9-ply nylon shell (300+G), were within the requirements of MIL-H-22995. It must be recognized, however, that all acceleration levels in excess of about 125G are considered unacceptable in accordance with the data presented in the section on Head Acceleration Limits.

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1. General
2. Helmet Materials
3. Helmet Accident Experience
4. Helmet Testing
5. Helmet Cooling
6. Football Helmets
7. Head Acceleration Limits
8. High Noise Level Communications

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8 - HIGH NOISE LEVEL COMMUNICATIONS

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APPENDIX I
DISCUSSION OF AUXILIARY HELMET EQUIPMENT

The factors which the U. S. Army considers necessary in providing headgear for aviators were listed previously in Approach to the Problem (page 5). Five of these items which lead to the installation of auxiliary equipment are discussed briefly, and their effects on the crash protective qualities of a helmet are noted below.

VOICE COMMUNICATIONS AND NOISE ATTENUATION

Six communications manufacturers were contacted during this study to determine the state of the art in regard to communications equipment. These contacts indicate that miniaturized, effective communications equipment is available; it remains for the purchaser to specify the operational acoustical environment and degree of speech clarity that is required or desired.

The noise level in some Army aircraft is 100 decibels and sometimes reaches 115 decibels (reference 14); therefore, any type of communications equipment must provide means of reducing cockpit noise to more tolerable levels.

A tentative list of requirements for a good communications system in U. S. Navy military aircraft should include the following factors as taken from reference 5.

1. The range of frequency response should be between 100 and 10,000 cycles per second with minimum distortion. The high frequency requirement is necessary for speech clarity, especially for consonant sounds.
2. Signal-to-noise ratio - A minimum of 15 decibels is suggested.
3. Noise attenuation - 30 decibels minimum between 300 and 1,200 cycles per second is suggested.

In regard to the selection of a microphone, it appears that a contact type is inferior to a condenser or noise-cancelling dynamic type. This statement is based upon the results of speech transmission tests conducted by the U. S. Navy School of Aviation Medicine at Pensacola, Florida⁵. These tests revealed a definite deterioration in the contact-mike speech clarity at 100 decibels and above.

The receiving equipment can be of the earplug type or of the earmuff type, as long as good noise attenuation and good voice communication are achieved. Attenuation up to about 40 decibels (depending on frequency) can be achieved with earmuffs. This value is superior to that of the earplug alone because of the reduction in bone conduction when the earmuff is used. It has been noted in reference 14 that a fungus growth resulted from the use of earplugs; thus, it may be necessary to consider the use of special materials for items contacting the skin to eliminate this problem.

Regardless of whether an earplug or an earmuff is utilized for voice communications, the device must be so designed that it reduces the injurious effect of an impact in this area.

One final point on communications is worth consideration. If the communications system is an integral part of the helmet, the helmet will probably always be on the wearer's head, where it can provide crash protection, whereas, if an independent communications system (similar to a telephone operator's) were used, the pilot would be less prone to make use of his helmet, especially in hot climates.

The experimental helmet developed in this program contains a provision for noise attenuating earmuffs which are filled with polyurethane foam. These earmuffs were supplied by Carter Engineering Company of Los Angeles, California; their literature indicates that these muffs can attenuate noise by 40 decibels in the range of 1,000 to 7,000 cycles per second frequency. They are of smaller size than the existing earmuffs in the APH-5 helmet and are much lighter in weight. The use of smaller earmuffs provides enough extra space for the incorporation of energy-absorbing material over the ear area. Although these earmuffs appear to be an improvement over those now used in the APH-5 helmet, they are not to be considered optimum equipment, since this area has not been investigated in this study.

INTEGRATED SUN VISOR

The operational advantages of a sun visor which is permanently attached to the helmet structure were not evaluated in this study. The compromises to the crash protective qualities of the helmet incurred by its use are discussed however.

1. Additional weight is added in the least desirable position, that is, in the frontal area of the helmet.
2. Additional thickness and weight will result in a higher center of gravity and higher susceptibility to rotational displacement.
3. The attachment of the visor, inside or outside the helmet outer shell, will result in injury producing obstructions unless extreme care and thought is put into the design. Some type of slide or rotational attachment must be provided; even if this hardware is made from plastic materials, the density is still many times over that of the energy-absorbing material which is displaced.

If the sun visor is a necessity, it should be made from a shatter proof material such as polycarbonate. The optimum approach would be to incorporate the sun visor (in retracted position) underneath the outer shell of the helmet so that a smooth outer surface is maintained, thus reducing snagging in glancing blows.

The experimental helmet model developed under this contract does not include a sun visor because of the compromises it offers to crash protection; however, a visor could be installed, underneath the outer shell, if necessary.

EYE PROTECTION AGAINST NUCLEAR WEAPONS FLASH BLINDNESS

A nuclear flash visor has been developed by the Navy and the Air Force; however, additional work in this area appears necessary before a completely operational unit compatible with crash protection is evolved. The Navy flash blindness protective helmet has a reduced field of vision over that obtainable with the APH-5; however, it does accomplish its purpose within the required time span. All of the comments made above with respect to the sun visor are appropriate to the flash visor problem.

OXYGEN AND GAS MASK PROVISIONS

The incorporation of oxygen and gas masks in a protective helmet is not considered a difficult task. The attachment of these items to the helmet should be accomplished with a minimum number of bolts, studs or snaps, so that the outer shell surface smoothness is maintained and so that no injury producing objects will be pushed through the energy-absorbing

material. It appears feasible to consider the oxygen mask as a face guard, that is, design it so that impact protection of the face is also provided.

BALLISTICS PROTECTION

A helmet which will provide protection against small arms fire is not currently compatible with light weight. In view of this incompatibility, it would appear more practical to provide ballistics protection in another manner than incorporating it into the helmet itself.

The double-shell concept proposed in this study permits the strengthening of the inner shell for increased ballistics protection with a lower weight penalty than for equal protection in a single-shell type, since the inner shell contains a smaller surface area than that of the outer shell.

APPENDIX II HEAD INJURY IMPACT SITES IN MILITARY AND CIVILIAN AIRCRAFT ACCIDENTS

In order to determine the probable location of the head injuries which will be experienced by air crewmen, 1,679 civilian and military accidents involving 1,953 occupants were reviewed. The statistical study, which was based on both military and civilian accidents occurring since 1952, was comprised of 637 accidents which yielded 896 occupant/cases of head injury. The civilian cases were selected from accidents involving aircraft similar in gross weight and performance to current U. S. Army aircraft. The information in this study has been used to determine the required area of coverage for a protective helmet.

OBJECTIVES

The objectives of this study were the determination of:

1. Location and frequency of head injuries and impact sites including facial injuries.
2. Type of head injury.
3. Causative agent or geometric surface onto which the head impacted.

LIMITATIONS

The cases studied were limited to the following:

1. Accidents involving nonjet, fixed-wing aircraft and helicopters.
2. Accidents involving aircraft without ejection seats.
3. Accidents which were considered potentially survivable.
4. Crew members only in military aircraft accidents.
5. All occupants in civilian aircraft accidents.

SOURCES OF ACCIDENT DATA

1. Civilian Accidents - The data used in this study were extracted from Aviation Safety Engineering and Research (AvSER) medical report forms. The completed forms are supplied to AvSER by Government agencies, State Aeronautics Commissions and State Police Organizations. No identification of injured individuals was made.

2. U. S. Army - The bulk of the data was collected from the medical reports of Army accidents in the AvSER files. The remainder was collected from the U. S. Army Board for Aviation Accident Research (USABAAR), Fort Rucker, Alabama.
3. U. S. Navy - A visit was made to the Naval Aviation Safety Center, Aero-Medical Department, Norfolk, Virginia, and the available data were recorded. No identification of the injured individuals was made.
4. U. S. Air Force - A visit was made to Norton Air Force Base, California. Accident records of selected aircraft, involving head injuries and/or helmet damage, were examined and recorded. No identification of injured individuals was made.

PRESENTATION OF DATA

All medical data used were reported by physicians and medical officers in charge of the injured persons; therefore, the location of the injury sites are considered reliable.

Two types of charts have been used to illustrate the location and frequency of head injuries. Figure 23 shows the head in quadrants, and illustrates both the surface injuries and the fractures of the total population. Figures 24, 25, and 26 show the location of the fractures for the total population. Skull fracture may be limited to the impact site; however, the fracture may also be remote from the point of external impact (contre-coup), or both local and distant damage may result from the same impact. Thus, some of the fracture locations illustrated in the charts may not be the actual site of impact.

Since the fractures in the Navy cases were reported by general areas only, the locations could not be represented in a fracture chart, but those that were applicable were included in the quadrant head chart.

The aircraft involved in the accidents studied are listed according to their normal seating configuration in Table 7. Note that all of these aircraft are about the same size as present U. S. Army aircraft.

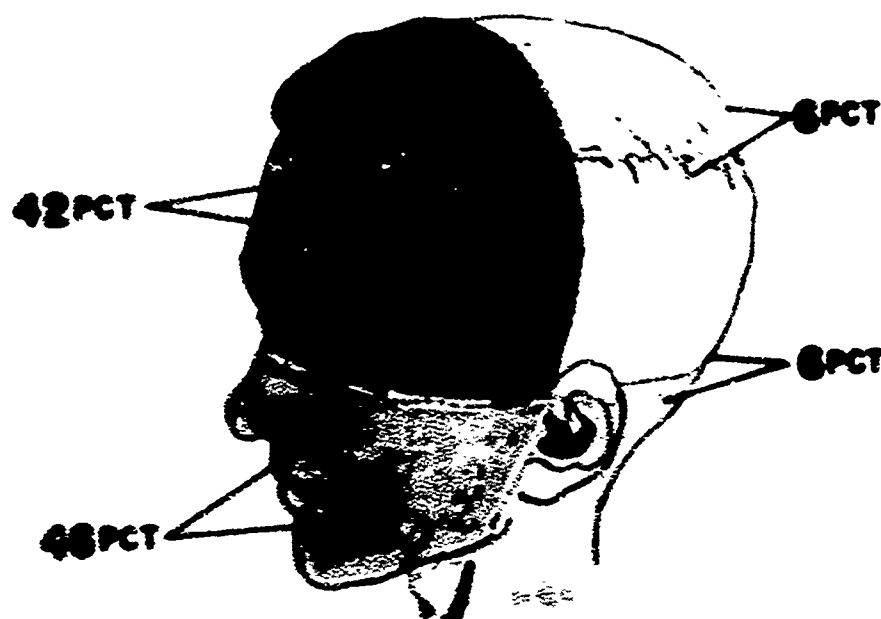


Figure 23. Location of Head Injuries to 896 Occupants in Accidents of Civilian and Military Aircraft.

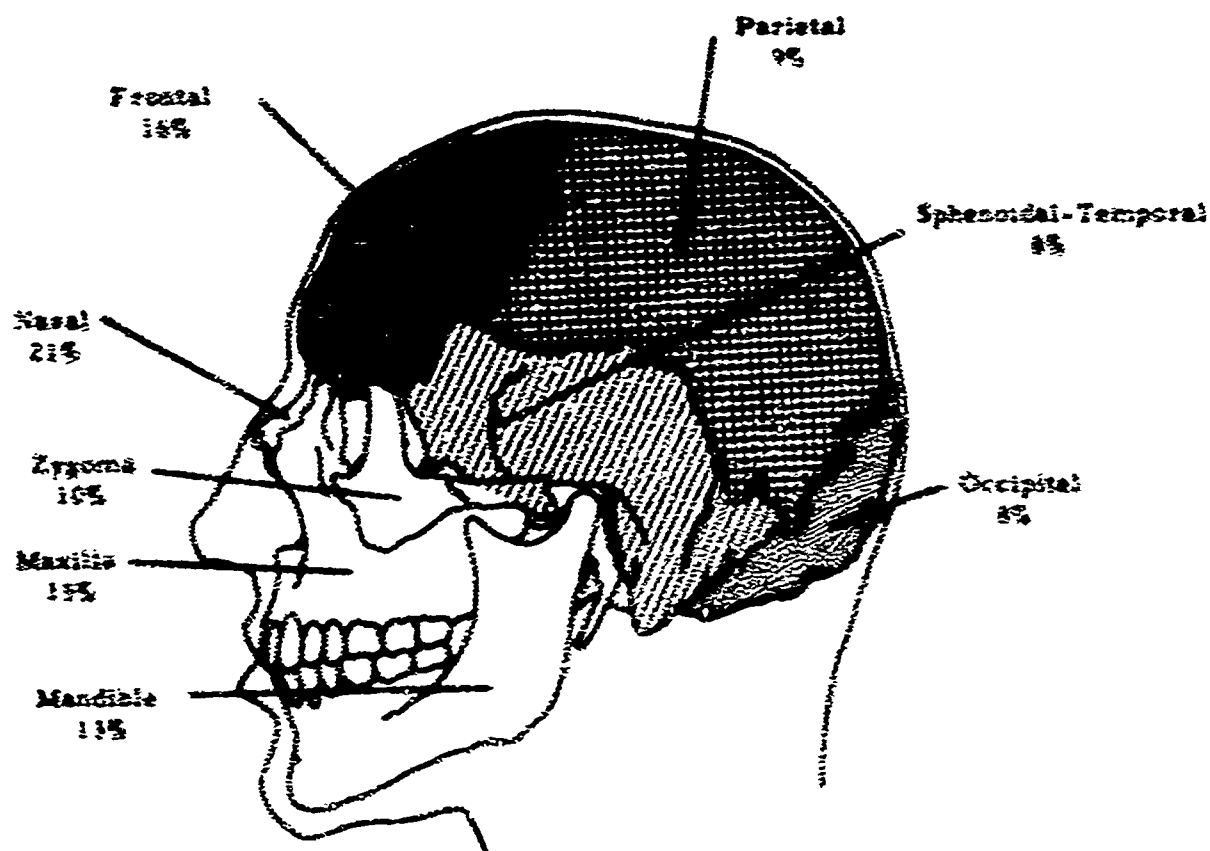


Figure 24. Location of 391 Fractures to 259 Occupants in Accidents of Civilian Aircraft. Note: Fracture percentages listed are for both sides.

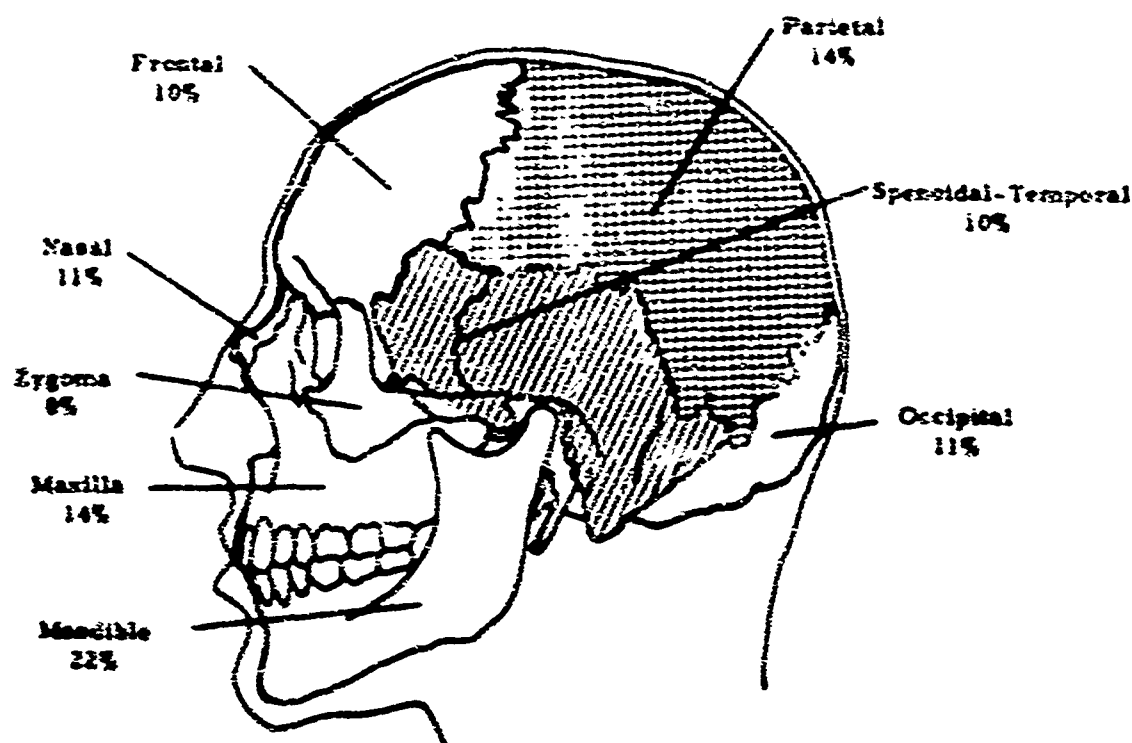


Figure 25. Location of 63 Fractures of the Skull and Facial Bones to 30 Occupants in Accidents of Army and Air Force Aircraft. Note: Fracture percentages listed are for both sides.

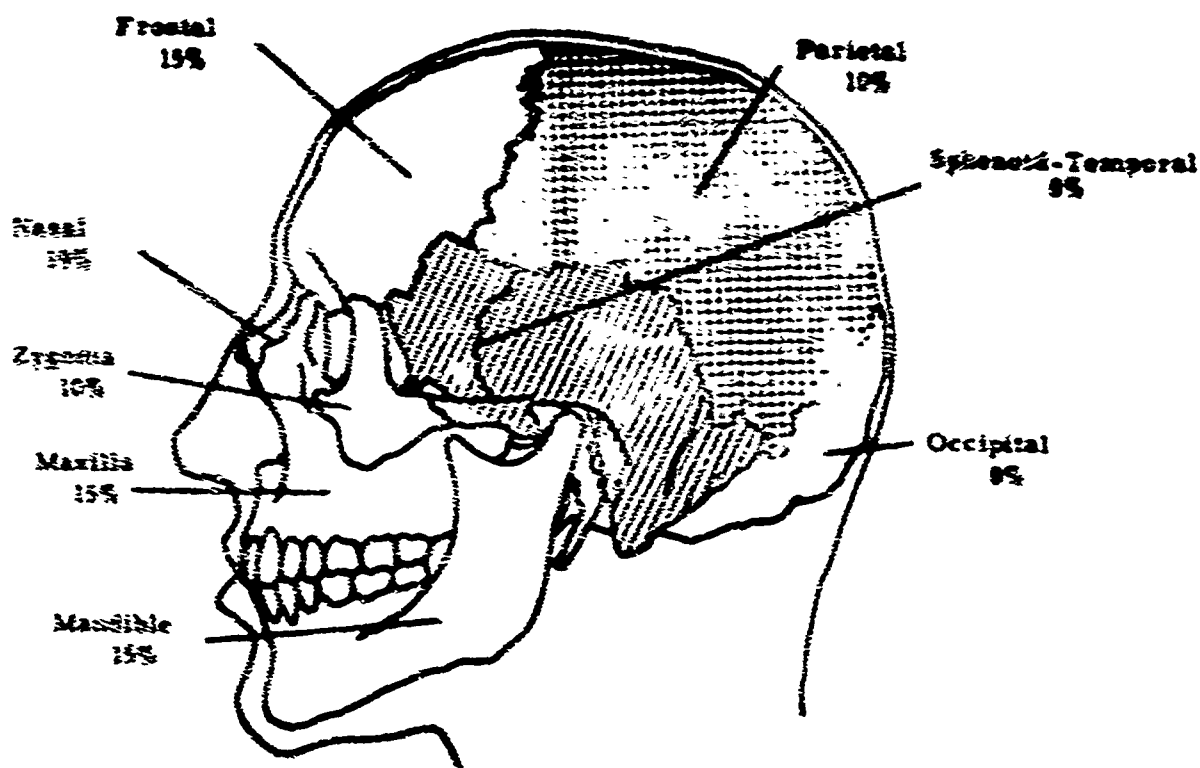


Figure 26. Location of 454 Fractures of the Skull and Facial Bones Involving 289 Occupants in Accidents of Civilian Aircraft. Note: Fracture percentages listed are for both sides.

TABLE 9
NUMBER OF AIRCRAFT AND SEATING FOR CASES USED IN THIS STUDY

<u>Civilian</u>		<u>Military</u>	
Seat Places	No. of Aircraft	Seat Places	No. of Aircraft
1	30	2	68
2	138	4	12
3	14	5	4
4	296	6	16
5	12	7	9
6-9	8	8	2
	<u>498</u> Total	9	1
		10	22
		11	1
		12	1
		18	1
		28	2
			<u>139</u> Total

Aircraft Type - Fixed-Wing
Gross Weight - 1,500-4,500 lb

Aircraft Type - 40% Fixed-Wing
- 60% Helicopters
Gross Weight - 2,400-29,000 lb.

RESULTS

The results are discussed separately for the civilian cases and the military cases.

Civilian

This group of accidents covers the period from 1952 through 1963. Review was made of 738 accidents involving 1,491 occupants; some type of head injury was reported in 758 of these cases. It is significant that over 50 percent of the occupants sustained some type of head injury. Only 701 of the 758 cases were used in this study because of inadequate information on the remainder.

The skeletal chart (Figure 24), showing the distribution of fractures for this group, indicates that with the exception of the nasal bone, fractures are predominant in the frontal area of the skull. The frontal bone sustained 16 percent of the fractures, and it is possible that a considerable number of the fractures in the occipital area were also caused by frontal blows.^{9A}

Internal Head Injuries - The medical reports in many cases indicated that some degree of cerebral concussion was sustained. Of the 701 cases, 358 (51 percent) are reported to have sustained some degree of cerebral concussion along with either fractures or lesser injuries. It was also observed that 75 percent of the above 358 cases sustained some period of unconsciousness.

Causative Factors of Head Injuries - The structural components of the occupant area which were directly or indirectly responsible for the head injuries were identified in 581 of the 701 civilian cases. These components are listed in Table 10 in a descending order.

TABLE 10
HEAD IMPACT SURFACES
(581 Civilian Cases)

Instrument or instrument panel	330
Windshield or windshield frame	87
Door posts or door frame	68
Back rest of front seat	65
Overhead structure or canopy	61
Side or forward braces	50
Control wheel	38
Controls	12
Cowling	12
Loose objects	8
Side cabin window	7
Miscellaneous	<u>22</u>
Total	760

The highest frequency component is the instrument panel (330), while the windshield area is next in order (87). These two areas are responsible for over half of the reported head strikes. Since these data apply to civilian accidents in which shoulder harnesses were not worn, it must be used with caution when considering military aircraft in which shoulder harnesses are standard equipment. The limited amount of injury data for the military aircraft shows frequent lateral impacts against door posts and window frames, especially in helicopter accidents. Thus, it appears that these surfaces may be involved in head impacts as often as the instrument panel in military aircraft.

Military

Army - The Army cases for the period 1956 through 1963 cover 256 accidents with 335 occupants. This group yielded 94 head injury accidents in which 128 occupants sustained some type of head injury.

Air Force - A review of the available Air Force accident case histories for the years 1960 through 1963 produced 11 accidents in which 29 occupants sustained some type of head injury. The injuries of the head were not specified for five cases and a total of 24 cases were used.

Navy - A review of applicable Navy records yielded 74 accidents for the period 1958 through 1963 with a total of 98 occupants. The specific site of head injuries was not available in many of these cases; however, 43 cases were specific enough to be used in the quadrant head injury chart (Figure 23).

Thus, 195 Army, Air Force, and Navy cases are included in this study. In the Army and Air Force cases, 63 fracture sites were noted as shown in Figure 25. It is significant that the parietal segment contains the largest percentage of fractures in the cranium. This is a reversal of the trend for the 391 civilian fractures (Figure 24), in which the frontal bone sustains the largest percentage of cranial fractures. Several factors may be responsible for this reversal. The first factor is the use of a shoulder harness by military personnel, which usage lowers the frequency of frontal head blows in many accidents. The second factor is the large percentage of helicopter accident cases in the military data in which the occupants are subjected to more lateral blows than with the civilian fixed-wing aircraft.

In this group of 195 head injury cases, the medical reports revealed that 113 (58 percent) experienced some degree of concussion. It was further indicated that out of the 113 concussion cases, 45 (40 percent) reported some period of unconsciousness.

In order to determine the degree of protection afforded by existing helmets, those cases in which they were worn were studied to determine whether they were retained during the crash and whether or not adequate protection was provided when retained.

Helmet information was specified in 77 out of 128 Army cases studied. Only 29 of the occupants wore helmets. Of the 29 wearing helmets, only 16 retained them during the crash. Of the 16 cases, 11 (69 percent)

were not injured in the area protected by the helmet, while 5 (31 percent) sustained injury in this area (2 minor, 1 moderate, and 2 fatal).

In the 61 remaining cases of the 128 studied, in which helmets were either lost or not worn, it is revealed that 7 (11.5 percent) were not injured in the area normally protected by a helmet and 54 (88.5 percent) received various degrees of head injury in this area (27 minor, 12 moderate, 2 severe, 3 critical, and 10 fatal). It is significant that injuries were reduced from 88 percent to 31 percent by those retaining their helmets, a reduction of 65 percent.

The Navy helmet cases could not be treated in the same manner as the Army cases due to insufficient information; however, some statistics are noted. The Navy group of 43 cases indicate that out of the 37 who wore helmets, 13 (35 percent) lost their helmets while the remaining 24 (65 percent) retained them.

In the Air Force group of accidents, it was noted that 12 helmet users received an impact to the head without receiving head injury; however, the area was not specified, and no impact sites could be charted.

Causative Factors of Head Injuries

Information on the impact surfaces causing head injury was available in 50 percent of the Army cases. Those components which were named as being directly or indirectly responsible for the injuries are listed in Table 11.

TABLE 11
HEAD IMPACT SURFACES
(64 Army Cases - Primarily Helicopters)

Windshield or bubble	16
Instrument panel	15
Side door or window frame	13
Control column, pedestal or cyclic stick	2
Radio box or jack box	7
Overhead structure	4
Miscellaneous	7
Total	71

It is noted that even though the population of this group is considerably smaller than the civilian cases, the same components are frequently struck. Since the windshield and instrument panel are relatively flat surfaces, it can be concluded that protection should be provided for flat surfaces and that the crushing strength of helmet liners should be selected accordingly.

All Cases

The overall frequency of injury for the entire group of civilian and military cases is shown in Figure 23. Note that the upper anterior and the lower anterior contain 88 percent of all injuries.

To determine if the area illustrated by Figure 27 requires helmet protection, injuries occurring in this outlined area (both sides) were tabulated in civilian, Army and Air Force accidents. The results show that only 4.7 percent out of the total 1,641 sites appear here. Fractures contribute 1.9 percent of the injuries in this area, and 94 percent of the fractures are located in the basal area of the skull. In a report describing the mechanism of skull fracture,^{9A} it was established that blows upon the frontal or lateral areas of the head are often the cause of basal skull fractures. Thus, the fractures in this area may be caused by impacts to other areas of the head. In either case, the small percentage of injuries implies that the need for helmet protection in this area is minimal.

Head fractures of the total population (civilian and military) are shown in Figure 26. Note that the facial bones receive a large percentage of the total fractures with 19 percent of the total in the nasal area, 15 percent in the maxilla, 15 percent in the mandible and 10 percent in the zygoma. Fractures in the cranium indicate that 15 percent occurred in the frontal bone, 10 percent in the parietal, 8 percent in the sphenoid-temporal and 8 percent in the occipital region. This fracture chart also indicates that the occurrence of fractures is greater in the frontal area. A comparison of the total fractures of the four areas of the facial bones with the four areas of the cranium reveals that 41 percent of the total fractures occurred in the cranium. Although only 41 percent of the fractures occurred in the cranium, it is significant that 88 percent of the fatalities in 829 head injury cases are attributed to injuries in this area. It is also informative that some degree of concussion was experienced in all cranial fracture cases; this fact reinforces the statement on this subject made by the authors of reference 9, as noted in The Head Acceleration Limits section (page 10) of this report.

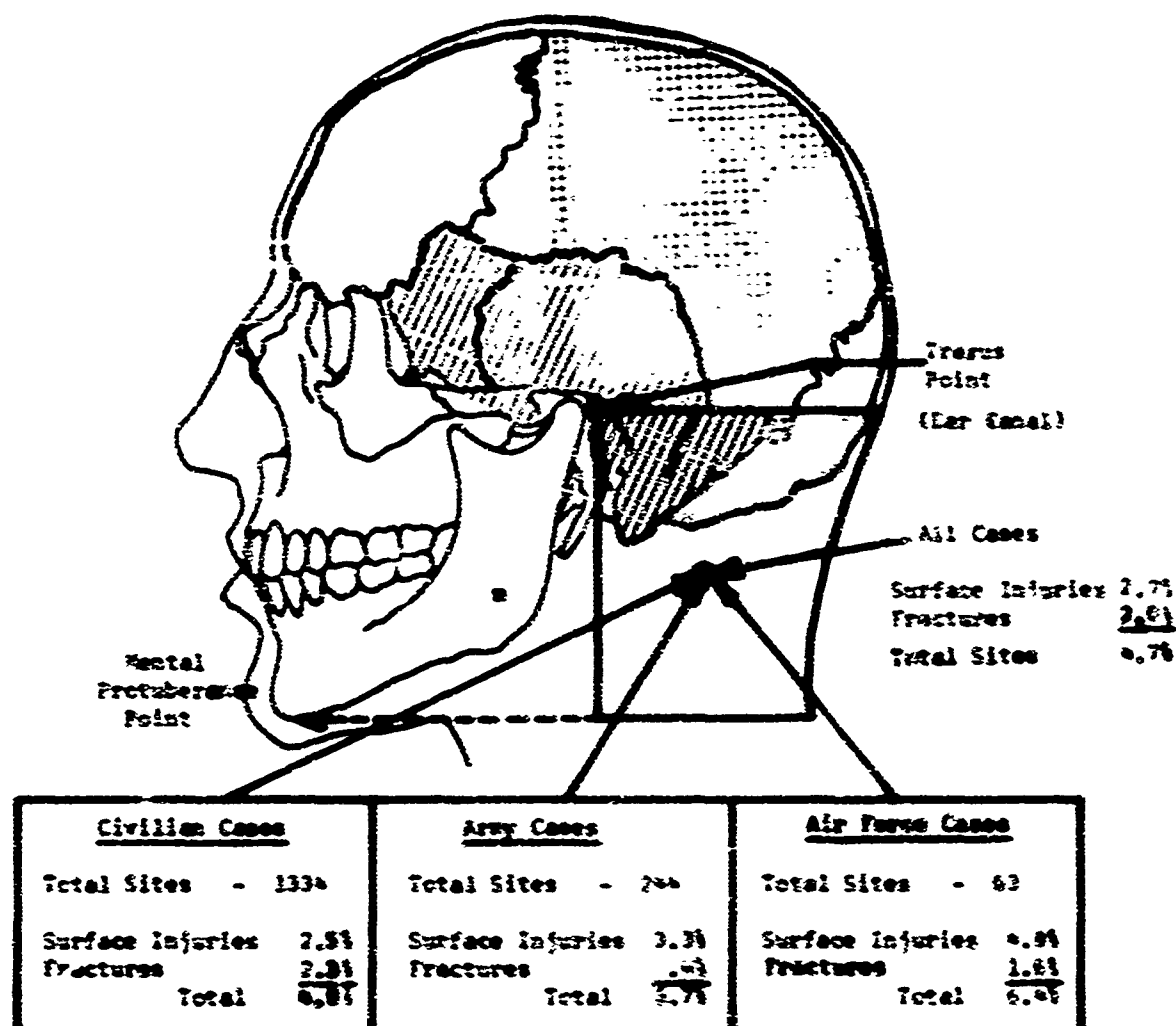


Figure 27. Location of Injury Sites Within Outlined Area (1,641 Injury Sites, 853 Cases).

CONCLUSIONS

1. Of 1,491 civilians involved in aircraft accidents, head injuries were sustained by 51 percent.
2. Some degree of concussion was reported in almost half of the head injury cases studied, and in these, 74 percent experienced some period of unconsciousness.
3. In those cases in which helmets were worn and retained on the head, head injuries were reduced by 65 percent compared with those cases in which the helmet was not retained or worn. (These data are based on a relatively small sample.)

4. Since 41 percent of all head fractures occur in the critical cranial area and all these cranial fractures are associated with some degree of concussion, it is vitally important that this area receive ample protection.

APPENDIX III
GEOMETRY OF PROBABLE HEAD IMPACT SURFACES
IN U. S. ARMY AIRCRAFT

The following aircraft were examined:

OH-23C	(H-23)	UH-19D	(H-19)
U-6A	(L-20)	CH-34C	(H-34)
TO-1D	(L-19)	U-8D	(L-23)
CH-21A	(H-21)	XH-40A	(Prototype UH-1)

OH-23C(H-23)

The sharpest surface in the cockpit appears to be the upper edge of the instrument console in front of the pilot. Two 0.15-inch-thick aluminum plates, to which the instruments are mounted, present a sharp edge of approximately 0.05-inch radius within reach of the pilot's head. Although deformation is expected on contact, it is doubtful that this sharp corner would be reduced significantly. Figure 28 illustrates contact of the helmet with this surface.



Figure 28. Helmet Impact Against Edge of Instrument Panel in OH-23.

U-6A (L-20)

The front door frame adjacent to the windshield is square-cornered (Figure 29); however, the sheet metal will easily yield, exposing the more ductile wood frame with a 1/8-inch radius. The main wing spar and its support structure (behind the pilot's head) is solid, with a 0.10-inch-radius edge covered only by a thin plastic cover; however, this surface would only become dangerous on rebound of the head. Figure 30 shows the control wheel of this aircraft which could be injurious if stationary. It is a 1-inch-diameter aluminum casting. The control wheel would probably yield on impact because it rotates for aileron movement.



Figure 29. Forward Door Post Edge and Wing Main Beam Support in U-6.



Figure 30. Control Wheel in U-6

TO-1D (L-19)

The instrument panel in this aircraft is 0.12-inch-thick aluminum plate whose upper edge is unprotected. It presents a sharper edge than the panel in the OH-23. Depending on the direction from which this panel is struck, it may be extremely dangerous and it is known that it has caused fatalities during accidents in which helmets were not worn.

Figure 31 shows the top edge of this panel. The front door frames are protected by 0.10-inch-thick aluminum sheet with a radius of 0.50 inch. Gasket plates are installed at the top of front door frames at the wind-screen V-brace attachment, as shown in Figure 32. This (0.50 x 0.50 x 0.06) aluminum angle presents a sharp corner; however, this surface will flatten to some extent when struck. A flap motor is attached to the ceiling behind the pilot's head and presents a 2.5-inch-diameter surface which can be struck on rebound. The motor is normally covered with a 0.50-inch thick sponge rubber pad which would offer some protection



Figure 31. Edge of Instrument Panel in O-1A Aircraft.
(View looking through the windshield from the outside.)



Figure 32 Forward Door Post and Upper Gasket Plates in T-10-1D.

CH-21A (H-21)

The forward cockpit window frame presents an 0.03-to 0.04-inch-thick aluminum edge of approximately 0.08-inch radius. This member has been struck by pilots in accidents with fatal results because of helmet fracture as documented in reference 1 in accident cases A, D and E. This frame flattened under impact and presented an edge of 1/2-to 1-inch width. All other windshield braces have the same radius of 0.08 inch and are sheet metal "hat" sections which will flatten somewhat under impact. The overhead panel presents a 0.50-inch-radius edge of aluminum sheet. The instrument panel is well protected with a fiberglass glare shield. Figures 33, 34, and 35 show the window frame, windshield braces and overhead panel, respectively.

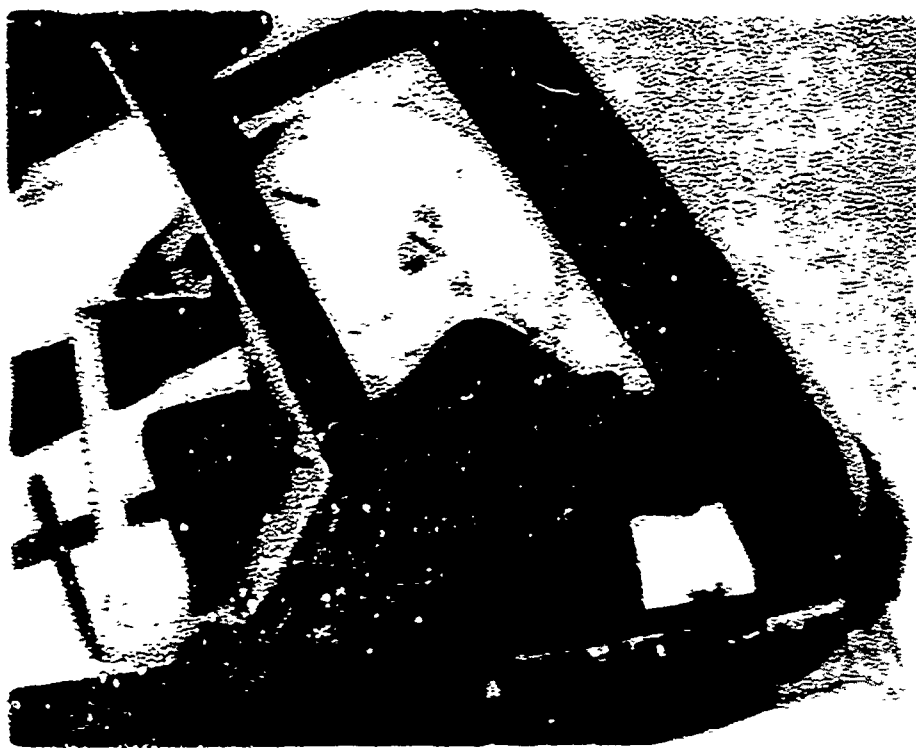


Figure 33. Forward Window Frame and Probable Helmet Impact Position in CH-21.



Figure 34. Helmet Impact Against Windshield Frames in CH-21.

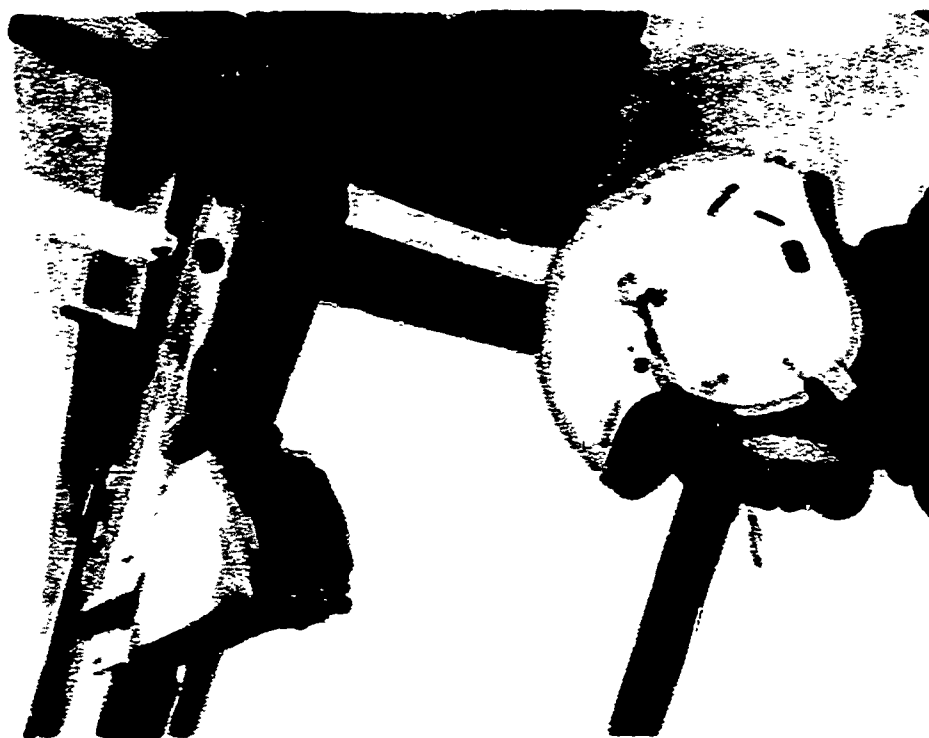


Figure 35. Helmet Impact Against Overhead Panel in CH-21.

UH-19D (H-19)

This aircraft has extremely close working quarters. The forward window-entrance frame is about one foot from the pilot's upright position. Thin gauge aluminum sheet around the door post, which is slotted to close the window (entrance), presents a 0.10-to 0.13-inch-radius edge, but it would flatten considerably on impact (Figure 36). All other windshield bracing is within 2 to 3 feet from the pilot's head, as may be seen in Figure 37. The radio compass is located overhead and mounted on a 0.06-inch aluminum bracket which, when struck from the proper direction, might have a piercing effect on a helmet (Figure 38). A radio junction box between the pilot and copilot seat can be struck on rebound (Figure 39), but the thin sheet would probably flatten under impact. The instrument panel is well protected by a fiber glass glare shield.



Figure 36. Helmet Impact Against Forward Window Entrance Frame in UH-19.

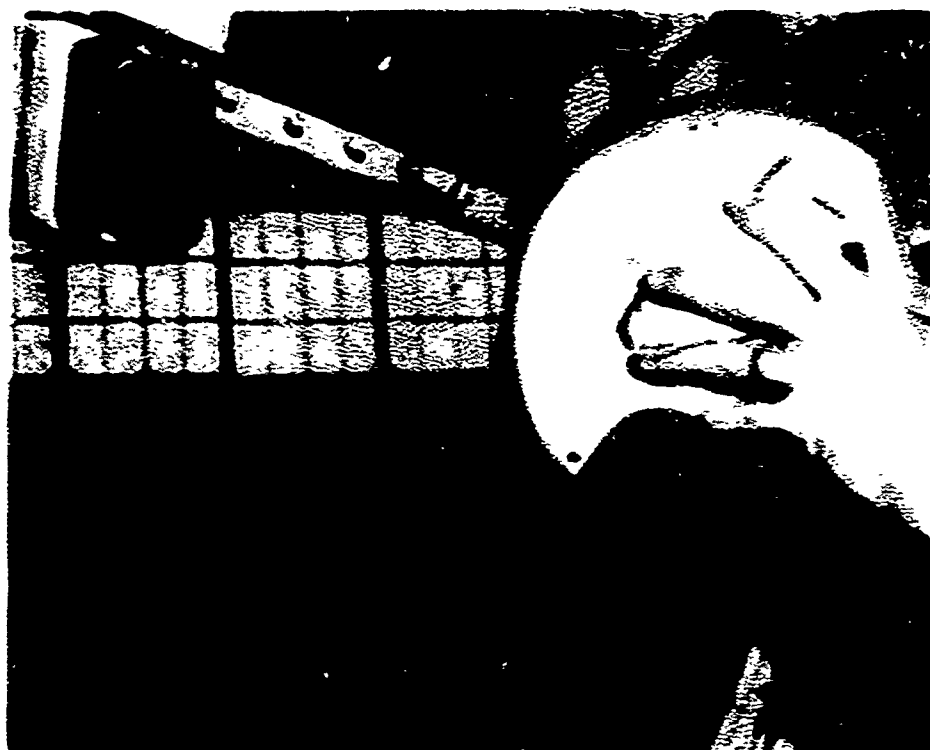


Figure 37. Helmet Impact Against Windshield Frame in UH-19.



Figure 38. Helmet Impact Against Edge of Radio Compass Mounting Bracket in UH-19.

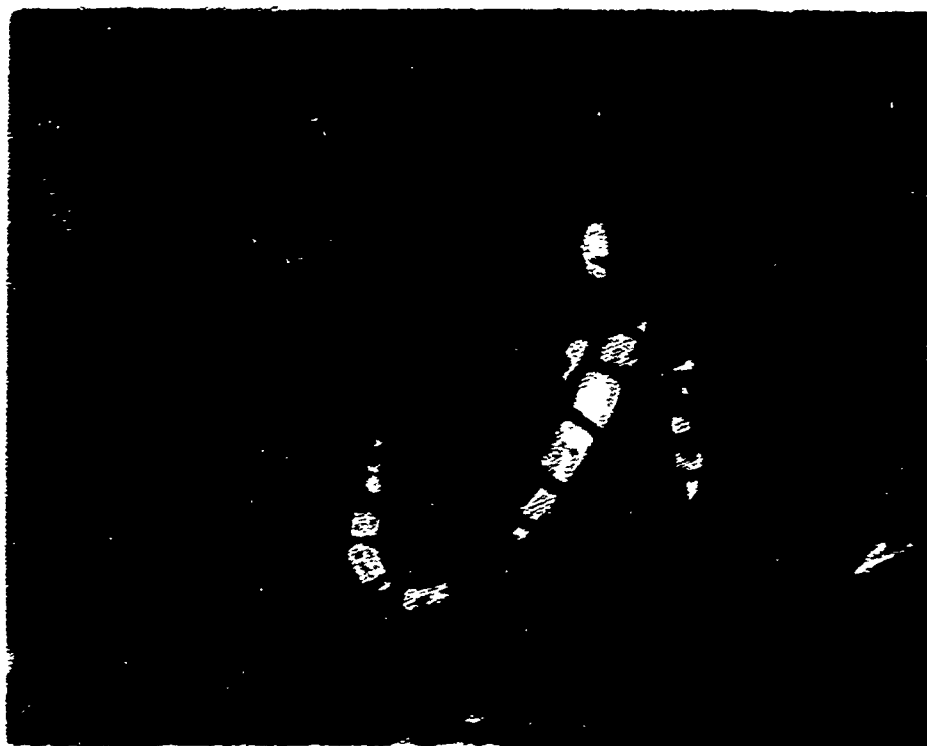


Figure 39. Position and Edges of Radio Junction Box in UH-19.

CH-34C(H-34)

This aircraft is somewhat similar to the UH-19, but has a slightly larger cockpit. The forward window-entrance frames contain a 0.50-inch-radius aluminum shield around a solid square framing (0.50 x 0.25 inch) with sharp (0.05 inch) corners. The overhead window frames are made of 0.030-inch aluminum channels attached to steel frames (see Figure 40). The overhead radio panel is square-cornered and would not yield on impact; however, it is not likely to be struck unless the aircraft is inverted. A rotor brake handle is also located on the pilot's side of the overhead radio panel. The cast iron handle, with a 1-inch-diameter steel knob, would not easily yield, but is not a likely striking surface unless inverted. A fuse box between the pilot and copilot seat is a striking surface on rebound as may be seen in Figure 41. The instrument panel is protected by a fiber glass glare shield.



Figure 40. Helmet Impact Against Upper Window Frame in CH-34.



Figure 41. Helmet Impact Against Edge of Fuse Box on Possible Rebound in CH-34.

U-8D (L-23)

Only two surfaces which could be potentially dangerous were found in this cockpit. Figure 42 shows the helmet impacting against a 0.25- to 0.30-inch-radius casting which is mounted on the ceiling for the attachment of the sun visor. The other surface is a switch junction box as shown in Figure 43 which is very rigid and contains a 0.12- to 0.15-inch-radius edge. The instrument panel is well protected as shown in Figure 43.



Figure 42. Helmet Impact Against Sun Visor Mounting Bracket in U-8 Aircraft.



Figure 45. Helmet Impact Against Switch Junction Box in U-8 Aircraft.

XH-40A (Prototype UH-1)

The most objectionable surface in the cockpit appears to be the forward door post. Accident experience has shown this to be a frequent impact site. The radius of the edge presented is approximately 0.10 inch; however, it will flatten somewhat on impact. The instrument panel is well protected by a fiber glass glare shield. Figure 44 shows a helmet impacting the door post.

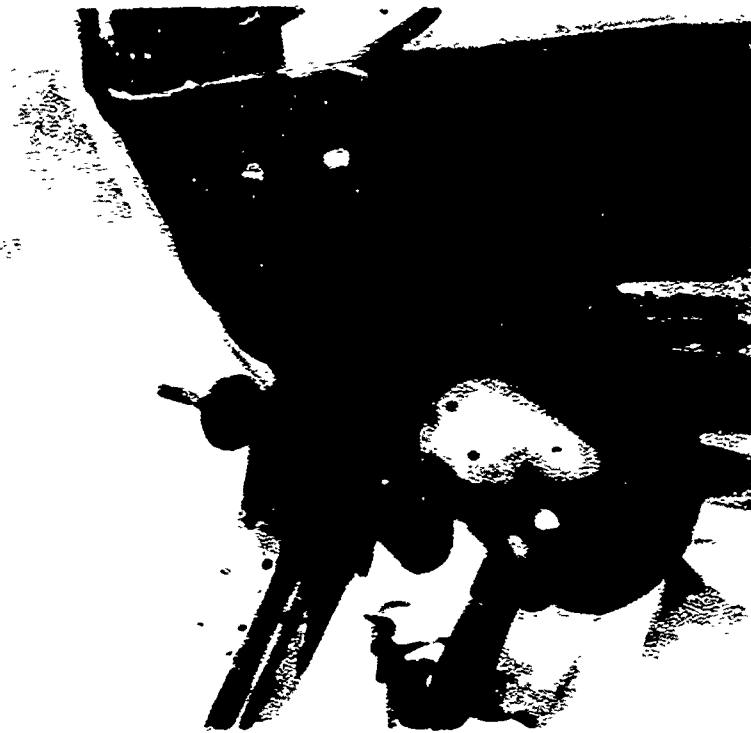


Figure 44. Helmet Impact Against Forward Door Post and Windshield Wiper Motor in XH-40 Aircraft.

SUMMARY

The most severe impact surfaces in light military aircraft contain a sharp edge or a rounded corner. The edge will usually bend somewhat upon impact on account of the thinness of the metal, modifying its threat to that of rounded corner. Exception may be found in the OH-23 and TO-1D; the upper edge of the instrument panel in these aircraft is unprotected and is not expected to flatten to any extent because of its rigidity. However, the chance that this edge will be struck perpendicularly is remote and this knifelike edge is not considered a primary threat.

It appears, therefore, that most surfaces within striking range in cockpits are of three types: (1) flat surfaces, such as an instrument panel, (2) corner surfaces, such as door posts and window frames, and (3) box corner surfaces, such as protrusions and corners of mounted boxes, etc. The striking surfaces of a drop device should, therefore, include the following shapes:

- 1 A flat surface
- 2 A 90-degree corner with a 0.25-inch radius
- 3 A box corner

The sharp, box-corner type surface is noted in only two of the eight aircraft examined and this type surface is not expected to exist in other current or planned Army aircraft such as the U-9, AO-1, CV-2, CH-47, XC-142, or the light observation helicopter in which environmental cockpit hazards have been considered more closely than in older aircraft. Thus, protection against a sharp surface appears to be less important than protection against the 90-degree corner and flat surfaces. This statement is reinforced by the data presented in Tables 10 and 11, of Appendix II, which indicate that less than 20 percent of the surfaces impacted can be considered sharp enough to classify as box corners.

Even though the very sharp box corner surface is not prevalent in undamaged cockpits, accident analysis indicates that aircraft structure does sometimes break or bend into the cockpit area so that jagged, sharp sections of stiff metal present a very severe impact surface. Thus, the helmet should provide some measure of protection against penetration by sharp objects, even though they are not the primary threat. The question still remains, should protection against very sharp box corner or cone surfaces equal the protection provided for corner and flat surfaces? Since there is presently little engineering data available on the impact velocities appropriate for the different types of impact surfaces, it is difficult to assess the relative importance of the cone test in helmet evaluation. Good resistance to penetration is intuitively desirable; however, it has been shown in Appendix II that the incidence of sharp surface impacts is small compared to corner or flat impacts. It thus appears that helmet performance against corner and flat surface impacts should not be compromised in attempting to attain equal protection against penetration in the sense that resistance at equal impact energy be required. As a matter of interest, Specification MIL-H-22995(WEP) calls for: (1) a 100-foot-pound^a impact with a 1/4-inch-radius spherical impactor and (2) a 10-foot-pound impact with a 60-degree cone, or a 10 to 1 energy ratio. The ratio should probably be nearer 2 to 1 and this can be approached without penalty as shown in this report.

^a Both head and helmet assembly and striking mass movable, and thus requiring about 50 foot-pounds to be absorbed by the helmet. See Supplement II.

in the tests conducted in this project, the box corner was simulated with a 93-degree cone with a radius of 0.06 inch at the apex. The cone test also demonstrates resistance to penetration from broken structure and other sharp objects.

APPENDIX IV HELMET SUSPENSION METHODS

A helmet can be suspended by two basic methods: (1) pads placed between the helmet and the head, and (2) a sling or net suspension which is attached to the lower periphery of the helmet shell.

PAD SUSPENSION

It is noted in reference 14 that the heat retention of the AFM-5 helmet is the greatest cause of complaints by users. The large fitting pads, in intimate contact with the skin, undoubtedly prevent perspiration evaporation. Thus, if pads are used, some method of allowing air circulation under and between them is necessary to achieve some degree of comfort. Probably the best method of achieving natural air ventilation, when pads are used, consists of grooving the pads vertically toward the crown so that the rising air can exit through several holes in the top of the helmet. Even this method, however, will probably inhibit free air movement to a greater extent than would a net or sling suspension.

If forced-air ventilation is considered feasible, then grooved or perforated pads appear to be more acceptable. A forced-air ventilation helmet, manufactured for use by aerial applicator pilots, was examined. The perforated and channeled pads used in this helmet are shown in Figure 45. The forced-air ventilation through the pads has proved to be beneficial for crop duster pilots because filtered air is forced into the helmet from its air base and channeled through the pads and downward over the face so that perspiration removal is enhanced.

The advantages of a pad suspension appear to be: (1) good stabilization through adjustment of pad thickness to fit the individual, and (2) easy replacement upon deterioration. The disadvantages appear to be: (1) heat retention, and (2) poor ventilation.

SLING SUSPENSION

During this study, several mock-ups of sling suspensions were made to assist in evaluating this concept. Typical systems are shown in Figure 46. Both of the systems shown in the sketches contain straps which would form the retention system of the helmet. Although the suspension systems

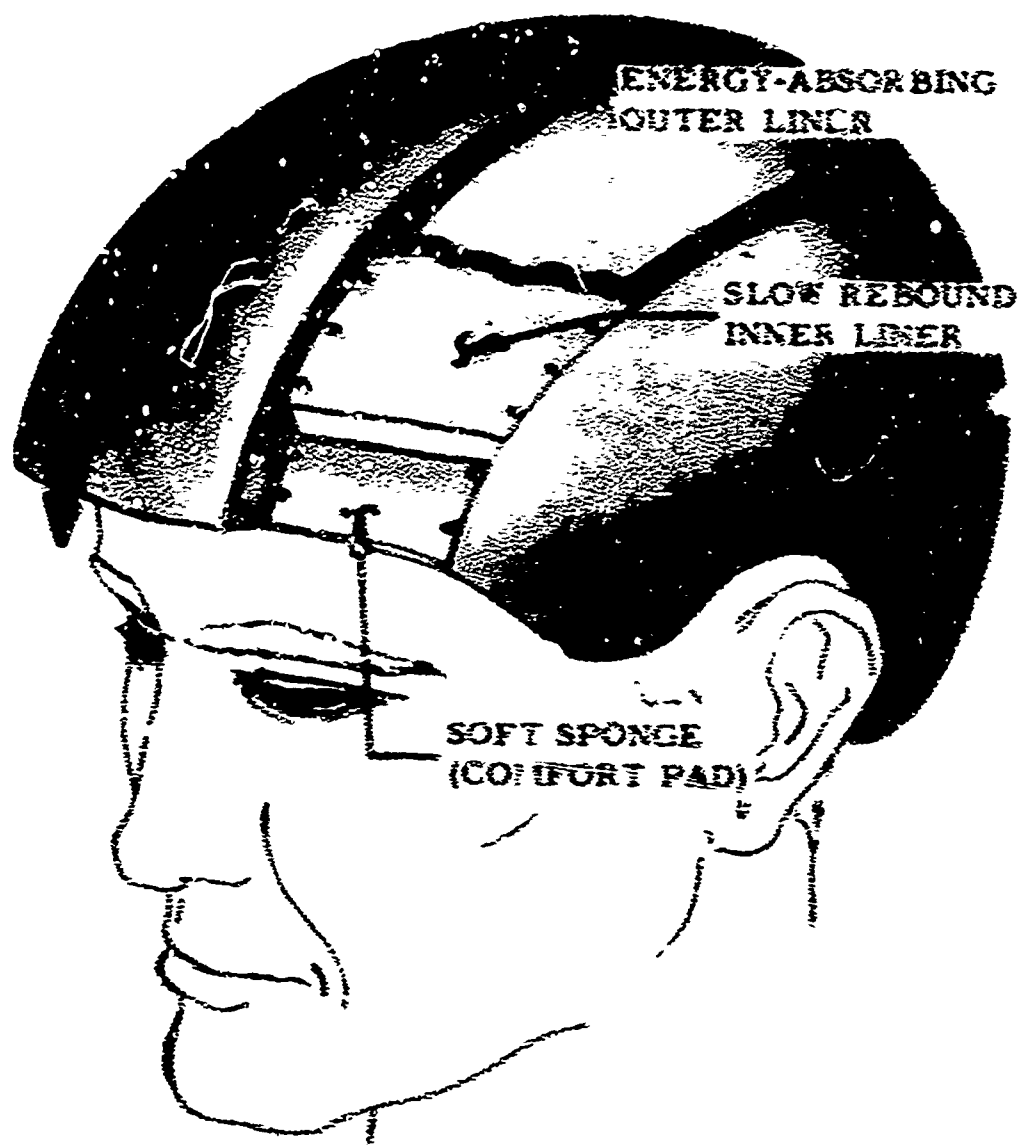


Figure 45. Perforated and Channeled Helmet Liners.



Figure 46. Sling Suspension and Retention Methods. (Sketch A illustrates a Net Retention System.) (Sketch B illustrates a Webbing Retention System.)

shown in the figure appear practical and feasible, it was decided to eliminate webbing pressure on the head by the use of an open weave net material. A net material yields good pressure distribution along with optimum natural ventilation, and the sweat band is eliminated. This suspension system is shown as it is installed in the experimental helmet in Figure 47. A crocheted net with 3/16-inch-diameter openings was selected. The crochet net tends to prevent unraveling. The material is manufactured by the Davis Mills Company, Lake City, Tenn. A preliminary evaluation of this net concept in the experimental helmet indicates that it will be comfortable and easily adjustable by the use of the drawstrings. The all-net suspension appears superior to any of the known suspension systems in use.

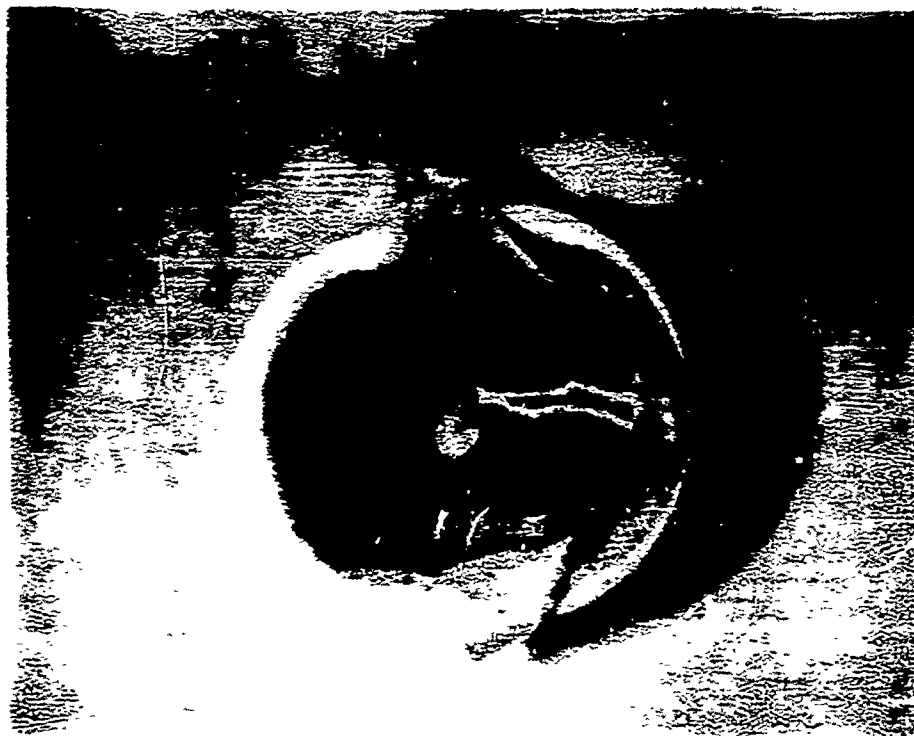


Figure 47 Nylon Net Suspension and Retention Harness Installed in the Experimental Helmet.

APPENDIX V HELMET RETENTION METHODS

It is noted in Appendix II that 13 helmets out of 29 worn were lost during accidents. Obviously, retention of the helmet on the head in a crash is as important as the force-attenuation properties of the helmet. A felt hat which remains in place would be superior to a helmet which becomes dislodged at the time of greatest need. There are two requirements for a retention system: (1) it must retain the helmet on the head during crash decelerations which are equal to the strength of the personnel restraint system, and (2) it must be comfortable. The first requirement will probably be met if the retention system is designed for the inertia force occurring in a decelerative pulse in which the head and neck are extended to the limit of survival in whole body decelerations. Certainly, larger forces can be expected if the whole body restraint system fails and the helmet is impacted in such a manner that a force acts upward along the front rim of the helmet; designing for such an impact does not appear practical until more is known about the neck and head tolerance to such forces. Thus, if the chin strap strength is based upon the inertia forces which may be applied, the design strength is obtained by multiplying the helmet weight by the expected inertia G factor:

$$45G^* \times 2.5 \text{ safety factor} \times 9.0\text{-pound helmet weight}^{**} =$$

450 pounds

The use of this strength value is tentatively recommended until more data are available.

The chin strap (or chin strap cover) of the retention harness must be thick enough to prevent creasing when forces are applied which tend to rotate the helmet laterally or longitudinally. The existing chin strap of 0.03 x 1 inch on the APH-5 is considered too thin; it is recommended that the thickness be increased to a minimum thickness of 0.06 inch. The existing 1-inch width of the APH-5 chin strap appears reasonable.

* 45G based upon planned restraint system strength for U. S. Army aircraft per reference 13.

** Based upon the QM interim 9-ply nylon helmet with oxygen mask.

Several mock-ups of retention concepts were integrated with sling suspension systems as previously shown in Appendix IV, Figure 46. Both of the webbing suspensions shown in these sketches appear to offer a snug fit around the base of the skull which is necessary to prevent forward rotation of the helmet; however, these systems are shown attached to the sweat band and since the sweat band is eliminated with an all-net suspension, the retention harness must be attached directly to the shell of the helmet. In order to fit the retention system as snugly as possible under the base of the skull, its attachment to the inner shell of a double-shell helmet is preferable for obvious reasons.

A net retention harness with a webbing chin strap was selected for use in the experimental helmet concept as shown in Appendix IV, Figure 47. The net harness is bonded to the outside periphery of the inner shell. It is adjustable through a drawstring at the rear. The net retention appears to be superior to webbing retention methods because it eliminates (1) localized pressure points around the base of the skull and (2) nape strap adjustment buckles.

The normal replacement requirements of the suspension and retention harnesses were not considered in the development of the experimental helmet described herein; however, replacement may be made by the use of a slotted track or extruded slide along the lower rim of the inner shell as shown in Figure 48.

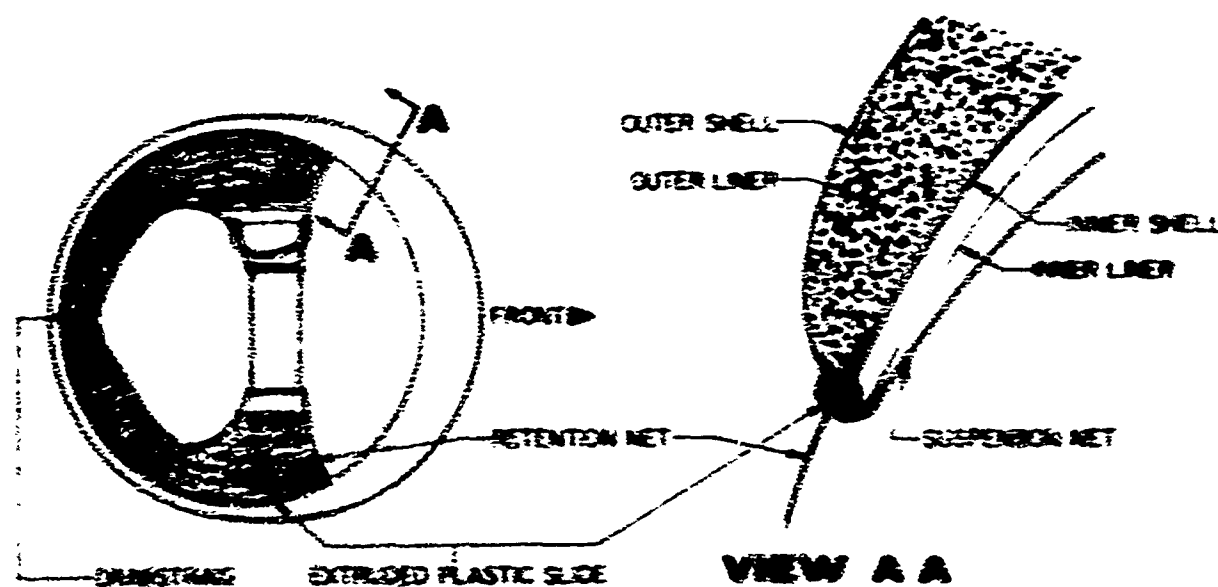


Figure 48. Proposed Method for Replacement of Net Suspension and Retention Harnesses.

The retention net would be trimmed with a bulbous edge so that it would be retained in the extruded slide.

The ability of the net suspension to fit the neck snugly and prevent forward rotation of the helmet from the head is demonstrated in Figure 49. It can be seen in the photograph that the forward edge of the helmet is riding on the top of the nose, but further rotation was not possible with an application of about 50-pound force. The 80-percentile helmet in the figure is fitted to a 50-percentile head and 45-percentile neck; therefore, an extremely loose fitting helmet is demonstrated. A larger head size would not permit as much movement as indicated here.



Figure 49. Photograph Illustrating the Retention Capacity of the Nylon Net Harness.

In conclusion, it can be stated that any retention harness should contain a peripheral tie around the base of the skull to prevent forward rotation of the helmet off the head in severe crash conditions.

APPENDIX VI HELMET SIZING (FIT)

The importance of the correct size helmet for each individual cannot be over-emphasized, since an incorrect size is detrimental to comfort and retention. A review of the literature to determine the variation in size and shape of the human head has not revealed information more complete than the Air Force study A Head Circumference Sizing System for Acceleration Design (WADD Report 60-631)¹⁵. This report is based upon the anthropometric data obtained from 4,000 flying Air Force personnel in 1956. The study reveals that the variation of the human head in size and shape is remarkable; for example, the ear position varies approximately 1 inch horizontally and vertically with respect to the front and top of the head. The head width varies by more than 1 inch and the head length varies by more than 1-1/4 inches. For a given head length, the head width will vary by as much as 1/2 inch.

The conclusion was drawn in the Air Force study that a sizing system based upon the head length and the head breadth, as basic dimensions, is less versatile than a head circumference sizing system because of the difficulty in obtaining accurate field measurements of head length and breadth; therefore, a sizing system based upon the head circumference only was recommended. This conclusion is probably valid if the clearance between the head and the helmet is not considered very important. It appears, however, that the maximum clearance between the helmet liner and the head is very important. With greater clearance, the amount of helmet rotation which can occur due to impacts tangent to the surface increases, and helmet retention is more difficult when large rotations are permitted.

The head length and head breadth clearances permitted by a 3-size circumferential and a 6-size, head-length and head-breadth sizing system were examined in the Air Force report. It was noted that if a 6-size, head-length and head-breadth system is used in place of the currently accepted 3-size circumference system, the head length clearance within a 3-size helmet will be reduced by fifty percent and head breadth clearance will be reduced by twenty percent. The percentage reductions stated are based upon equal percentile coverage for the flying population.

The following factors should be considered before the sizing system for aviator helmets is selected: (1) optimum fit enhances helmet retention due to the reduced clearances, especially for a nape strap

harness; (2) optimum fit reduces size and weight to the minimum for each individual. It is concluded that a 6-size head-length and head-breadth system significantly reduces clearance dimensions, and this system is recommended especially for helmets with nape strap retention systems. If the supply problems of stocking 6 sizes are considered prohibitive, then the second choice would be a 4-size system based on head circumference in which the sizes are called small, medium, large, and extra large. It will be more important to use a 6-size length and breadth sizing system if the nape and chin strap continue in use as the primary method of helmet retention. If a peripheral "collar" type retention system is adopted, the effect of fit on retention is reduced, and the 3-size circumference system should be acceptable.

APPENDIX VII HELMET COMFORT AND COOLING

Comfort is defined by Webster as "a state of ease and quiet enjoyment, free from worry, pain, etc.". Obviously, a helmet cannot provide this blissful state; therefore, comfort in an aviator helmet must be defined as minimizing the discomfort of carrying a weight on the head. The helmet wearer should tolerate a certain degree of discomfort if convinced of the additional safety provided by its use.

In order to provide a minimum amount of discomfort, the following items should be considered in the development of a helmet: (1) minimum weight, (2) minimum moment of inertia, (3) minimum pressure on the head due to helmet weight, (4) helmet center of gravity coinciding with head center of gravity as nearly as possible, and (5) a comfortable temperature and humidity level. The first four items are discussed in the main body of this report, but temperature and humidity are considered here.

Most helmets should be comfortable in low temperature environments because of the excellent insulating properties of the energy-absorbing materials. Of course, the excellent insulating properties work in reverse in high temperature environments, and the outflow of heat from the head is retarded unless heat rejection is accomplished through better ventilation.

Several methods of cooling a helmet can be considered such as (1) natural ventilation, (2) forced-air ventilation, (3) refrigeration by a circulating fluid, and (4) thermo electric cooling. None of the methods of cooling were developed in this study; however, natural ventilation cooling was considered and a test was conducted to determine what benefit could be gained from ventilation holes with a total area of 3 square inches in the aft portion of the helmet crown. An area of 3 square inches does not compromise impact protection to any extent since it is shown in Appendix II that a low frequency of injuries occurs in this area. The temperature tests are described in this section as follows:

HELMET TEMPERATURE MEASUREMENTS WITH AND WITHOUT VENTILATING HOLES

Test Article Description - Two large size helmets manufactured for the Air Force by Consolidated Controls Corporation were used in this

experiment. The helmets were lined with 0.25-inch-thick vinyl foam pads in the front top and back. The helmets were cut off at 6.5 inches from the top at the ear canal (tragus) location as shown in Figure 50. The sling suspensions in the helmets were unmodified and they were adjusted to give approximately 0.75-inch clearance in the crown of the helmet between the vinyl pad and the sling suspension.

Provision was made to install a thermometer in the air space between the head and the crown of the helmet. A thermometer with 0.2 degree C graduation was used so that accurate temperature readings could be obtained. The helmets were designated A and B. Helmet B was drilled with four 1-inch-diameter holes on 3-inch centers. The test article is shown in Figure 50.

TEST PROCEDURE AND RESULTS

Test No. 1 - This test was performed indoors under controlled conditions to evaluate the temperature difference inside helmets A and B due to body heat alone.

The ambient room temperature was noted at the beginning of each test. The thermometer reading inside the helmet was recorded every five minutes until the temperature stabilized. The temperature versus time data for this test are plotted in Figure 51. It can be seen that the ventilated helmet B was about 1.5 degrees C (3 degrees F) cooler than the unventilated helmet A.

Test No. 2 - This test was performed outdoors to evaluate the effect of high ambient temperatures on the temperature difference inside helmets A and B. The test procedure was identical to test No. 1 except that the helmets were exposed to the sun for enough time to elevate their temperature to ambient conditions prior to donning.

The results of test 2 are also shown in Figure 51. The fluctuations noted are the result of gusts of wind ventilating and cooling the helmet interior rapidly. The temperature readings were stopped after 45 minutes because stabilized readings were not obtained as with the indoor tests. It can be seen that the average temperature difference between helmets A and B is about 1.0 degree C (2 degrees F).

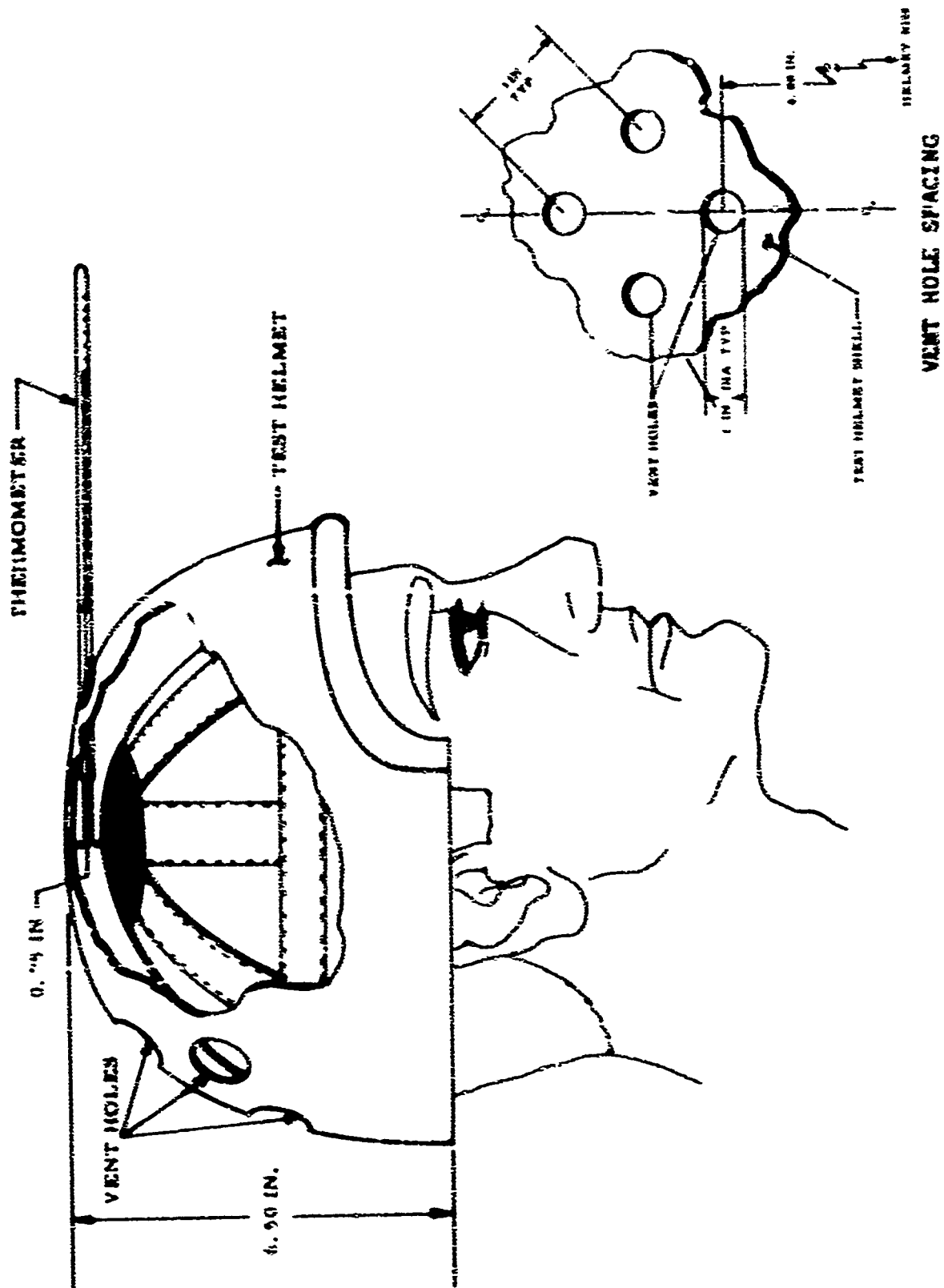


Figure 50. Test Specimen - Natural Ventilation Temperature Measurement.

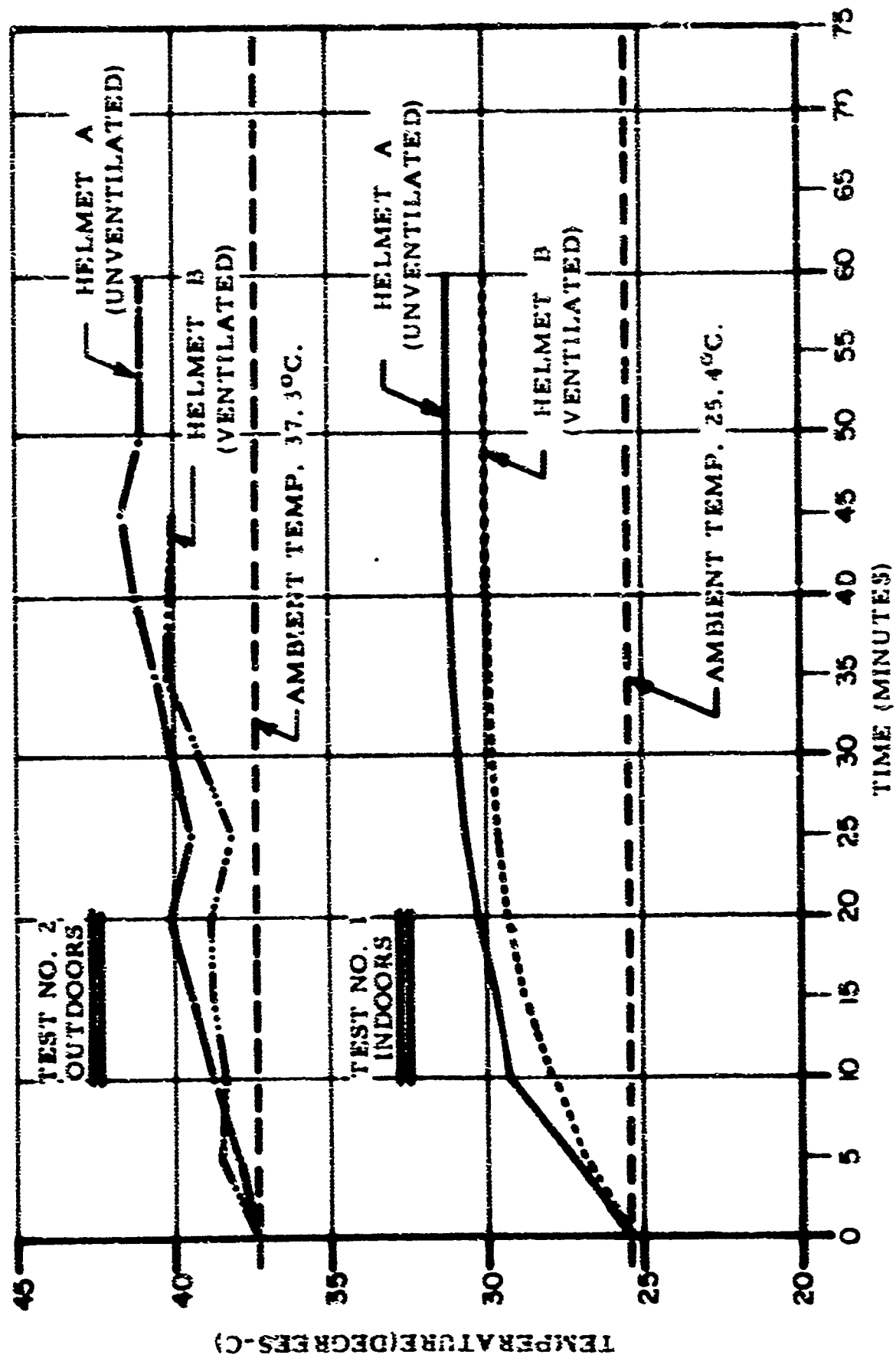


Figure 51. Test Results - Natural Ventilation Temperature Differences.

The small temperature difference noted between the ventilated and unventilated helmets alone may not justify ventilation, however, the beneficial effect of perspiration evaporation due to ambient air movement may be more important than the small temperature difference. In view of the low (approximately 20%) humidity conditions under which the tests were conducted, the benefits of perspiration evaporation could not be evaluated. It may be that the upward movement of air in humid climates would be helpful in perspiration removal. Further tests with varying humidity may be necessary to determine the maximum benefits obtainable with natural ventilation.

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13. ABSTRACT The major crash survival variables affecting the design and testing of U. S. Army aircrewmens helmets are presented and discussed in this report. Such factors as head acceleration limits, impact velocity, impact surfaces, impact sites, suspension and retention harnesses, helmet ventilation, impact test methods and structural concepts are considered. An examination of all available data on the tolerance of the human head to deceleration was conducted. Consideration was given to an analysis of acceptable design limits. A parallel study of head injuries occurring in aircraft accidents was conducted to determine the significant injury areas of the head and correlate this to protection area and techniques. A cockpit survey was conducted to develop criteria for testing the helmet and liner materials. Consideration was given during the program to a preliminary investigation of helmet retention systems and head cooling techniques. A series of instrumented drop tests was conducted to investigate various helmet design concepts and materials. Double-shell and single-shell helmets of nearly equal weight were analyzed. The advantages and disadvantages of three different methods of helmet impact testing are discussed.	

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